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Shenoy

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(54) **METHOD FOR FORMING
ACCUMULATION-MODE FIELD EFFECT
TRANSISTOR WITH IMPROVED CURRENT
CAPABILITY**

(58) **Field of Classification Search**
USPC 438/259, 270, 274; 257/328, 330,
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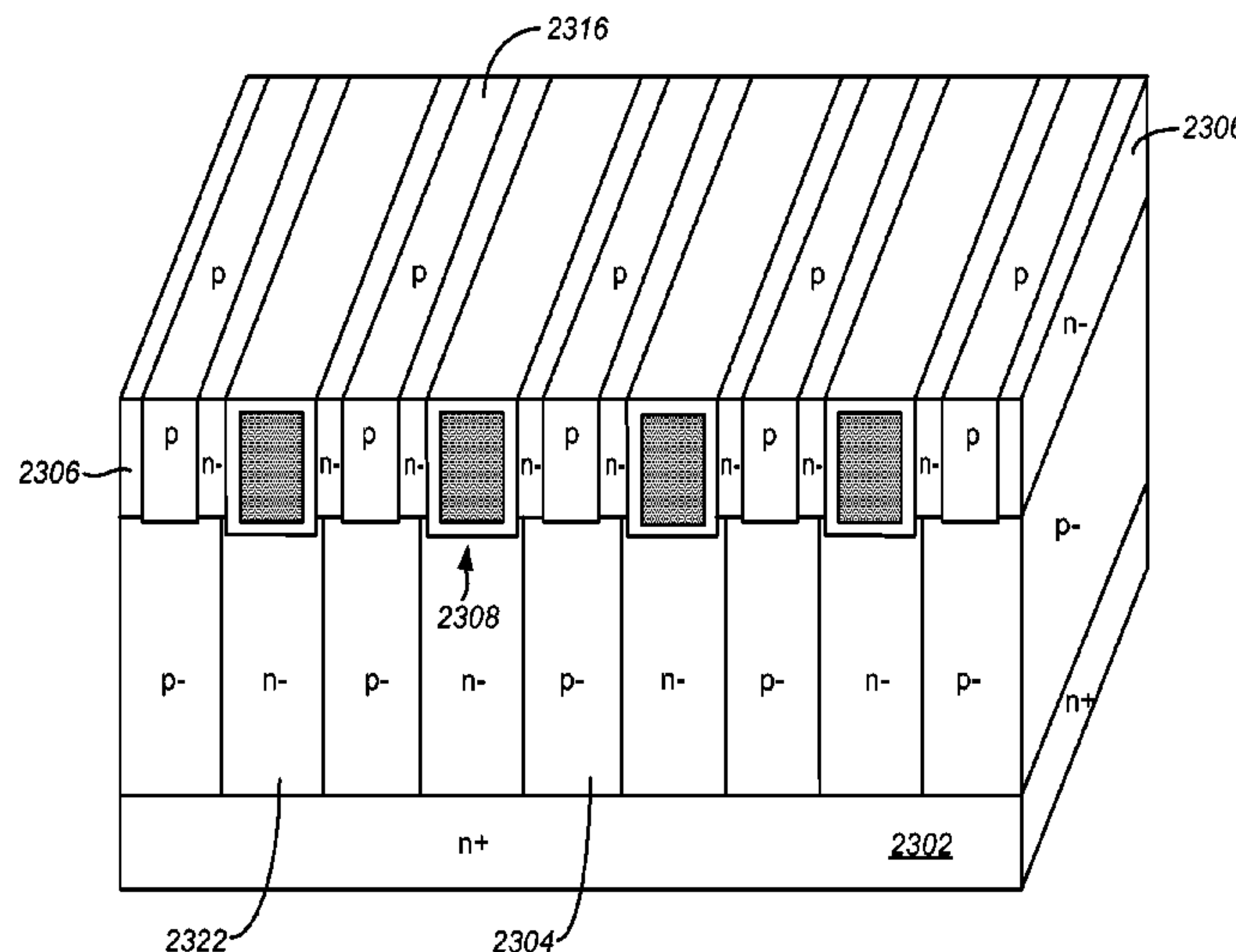
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(57) **ABSTRACT**

A method of forming an accumulation-mode field effect transistor includes forming a channel region of a first conductivity type in a semiconductor region of the first conductivity type. The channel region may extend from a top surface of the semiconductor region to a first depth within the semiconductor region. The method also includes forming gate trenches in the semiconductor region. The gate trenches may extend from the top surface of the semiconductor region to a second depth within the semiconductor region below the first depth. The method also includes forming a first plurality of silicon regions of a second conductivity type in the semiconductor region such that the first plurality of silicon regions form P-N junctions with the channel region along vertical walls of the first plurality of silicon regions.

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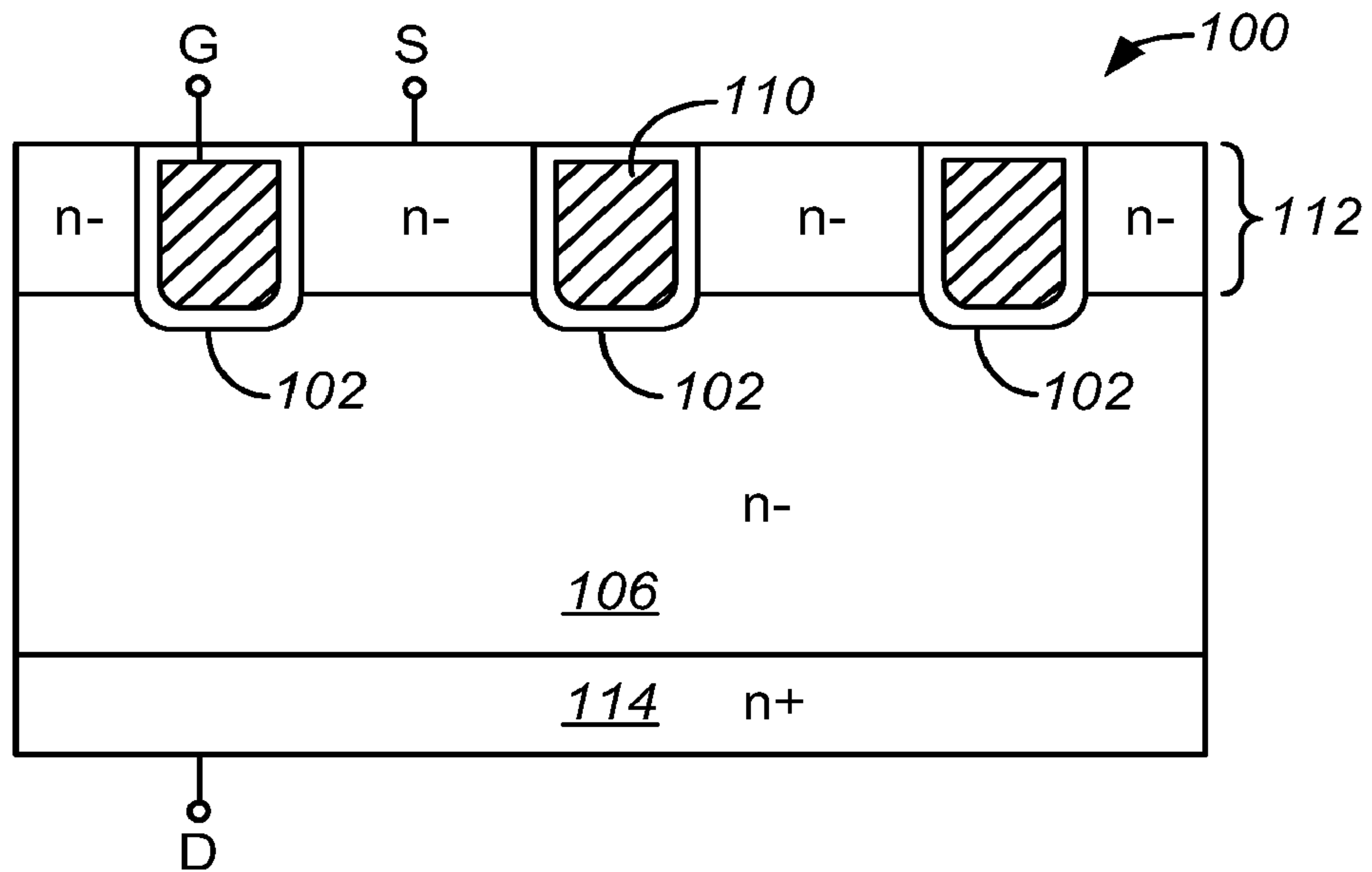


FIG. 1
(Prior Art)

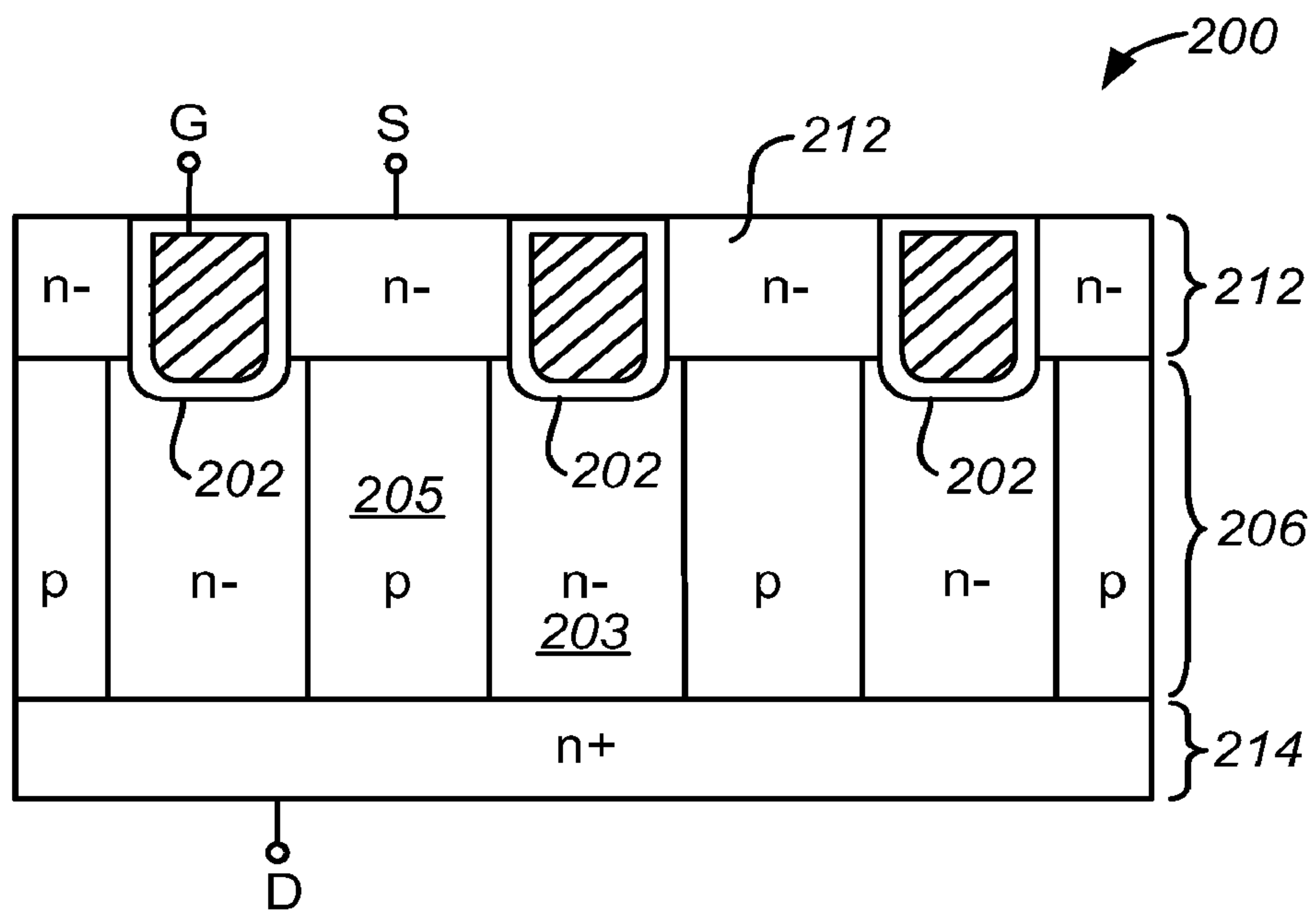


FIG. 2

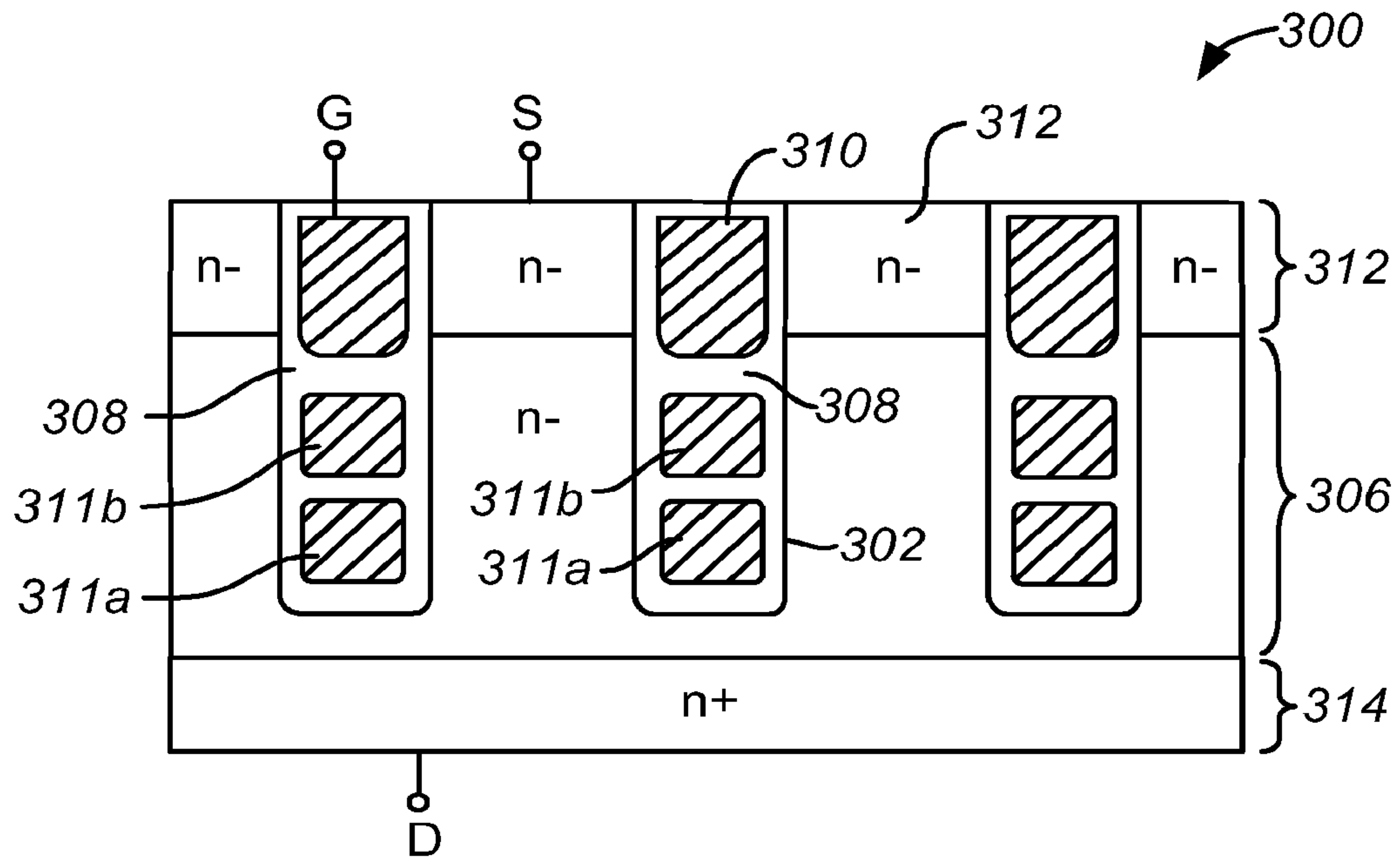


FIG. 3

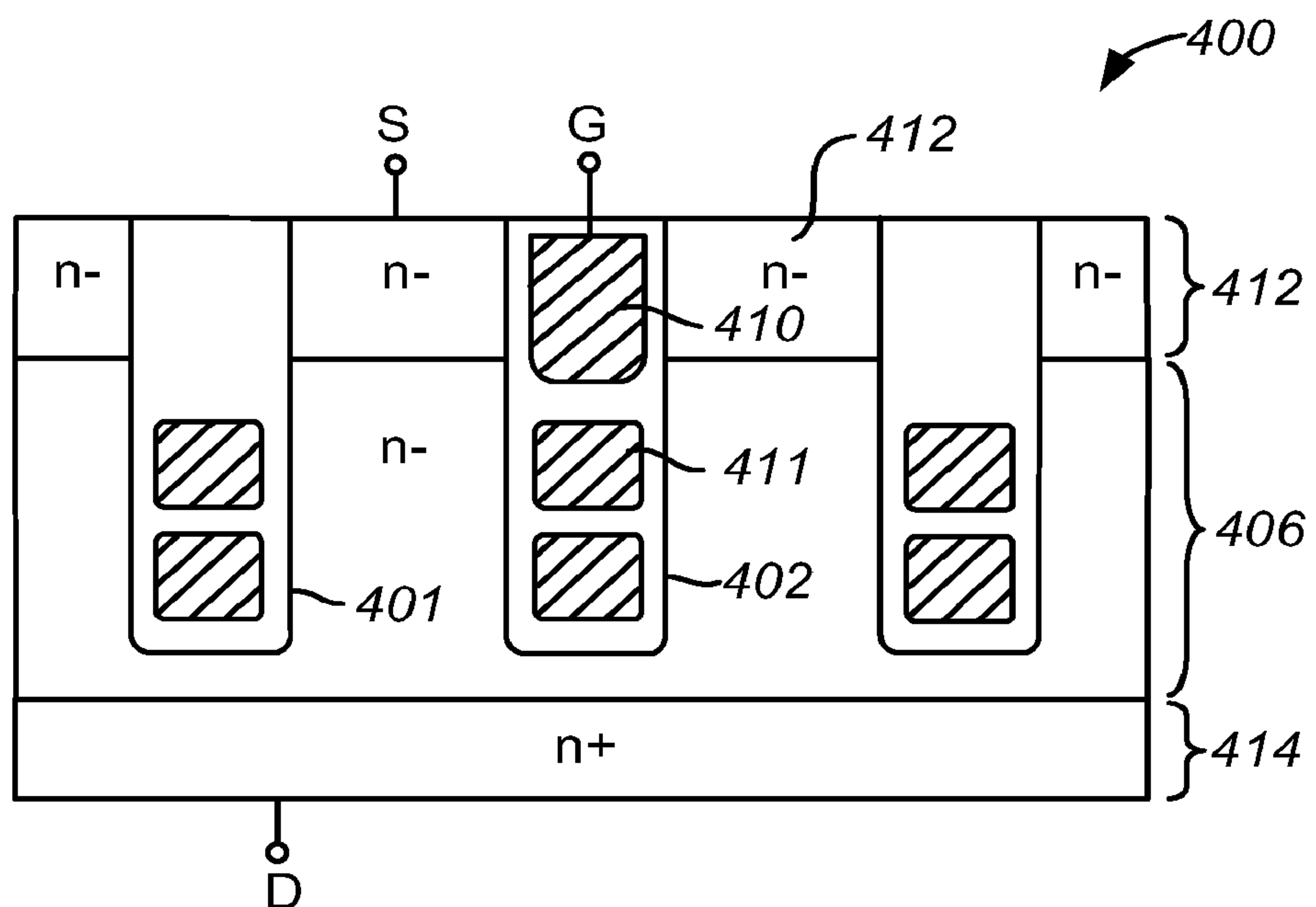


FIG. 4

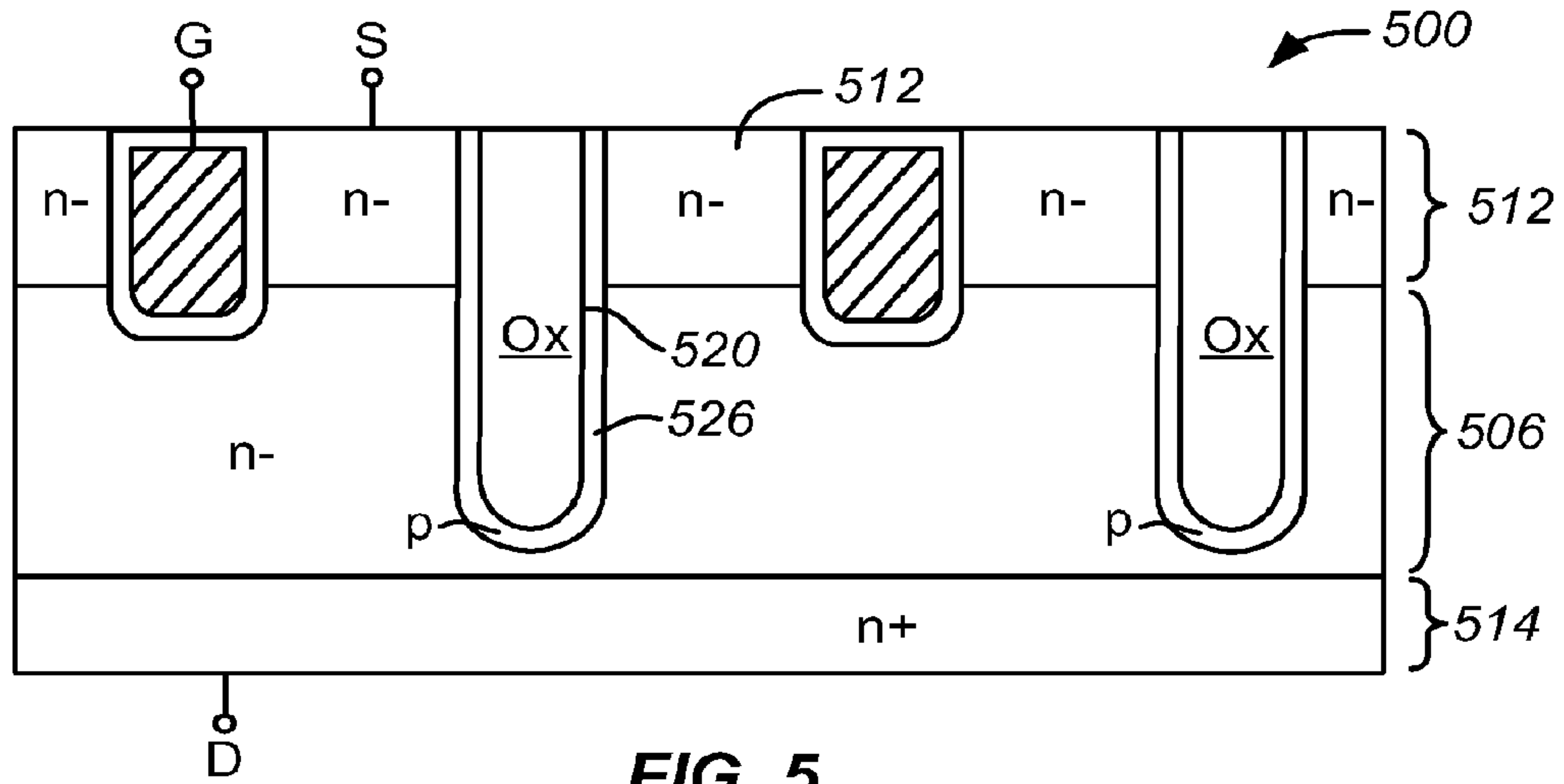


FIG. 5

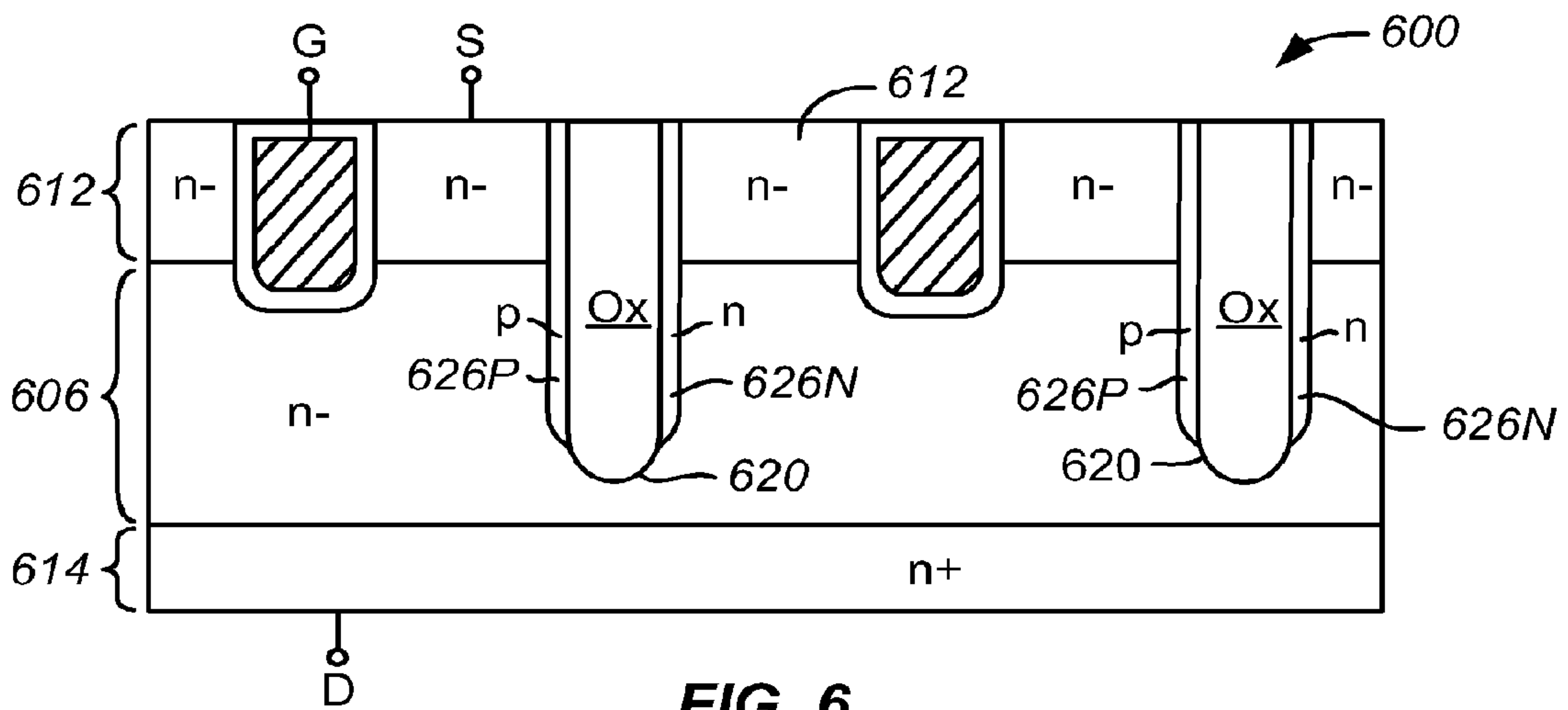


FIG. 6

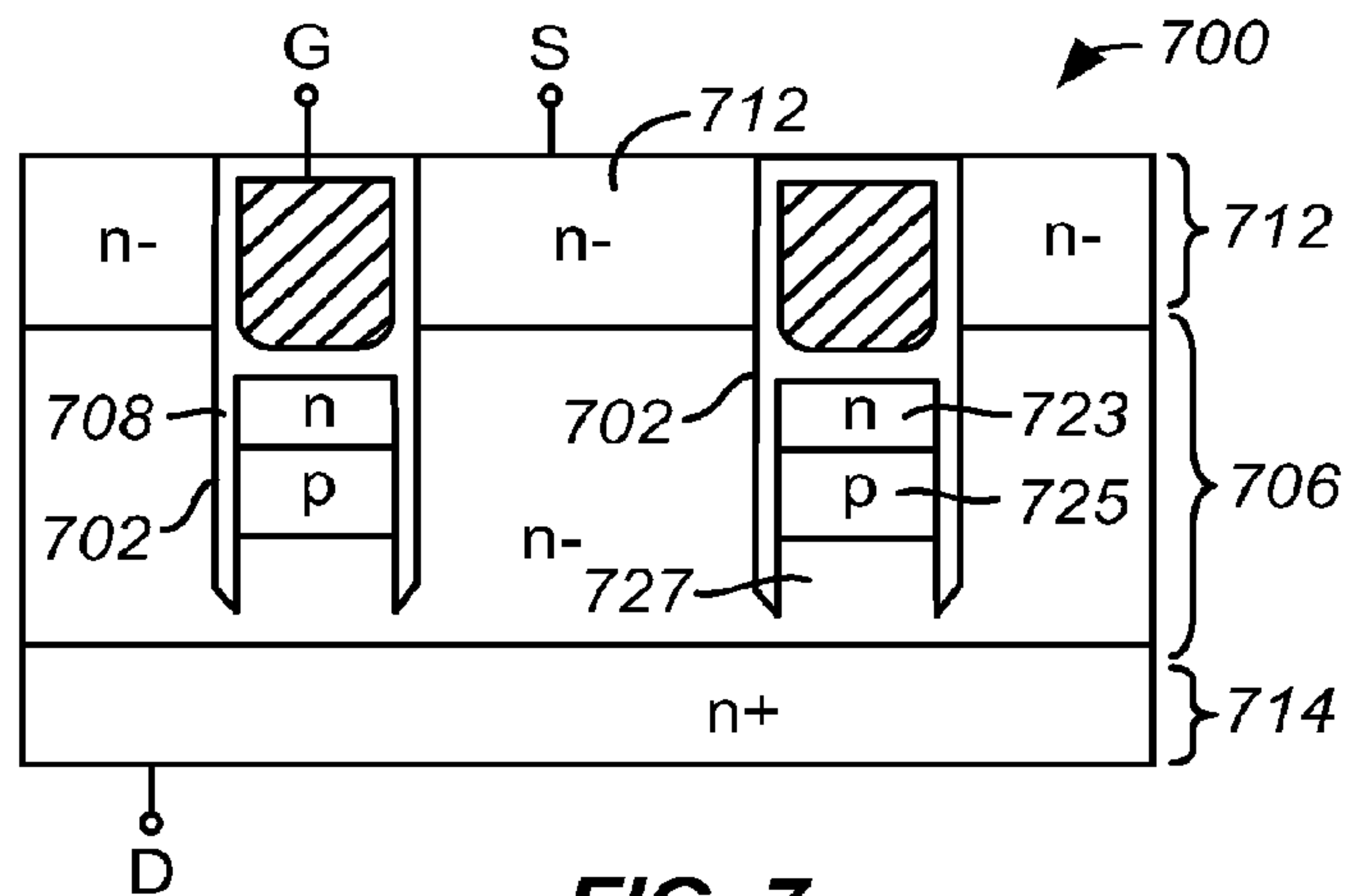
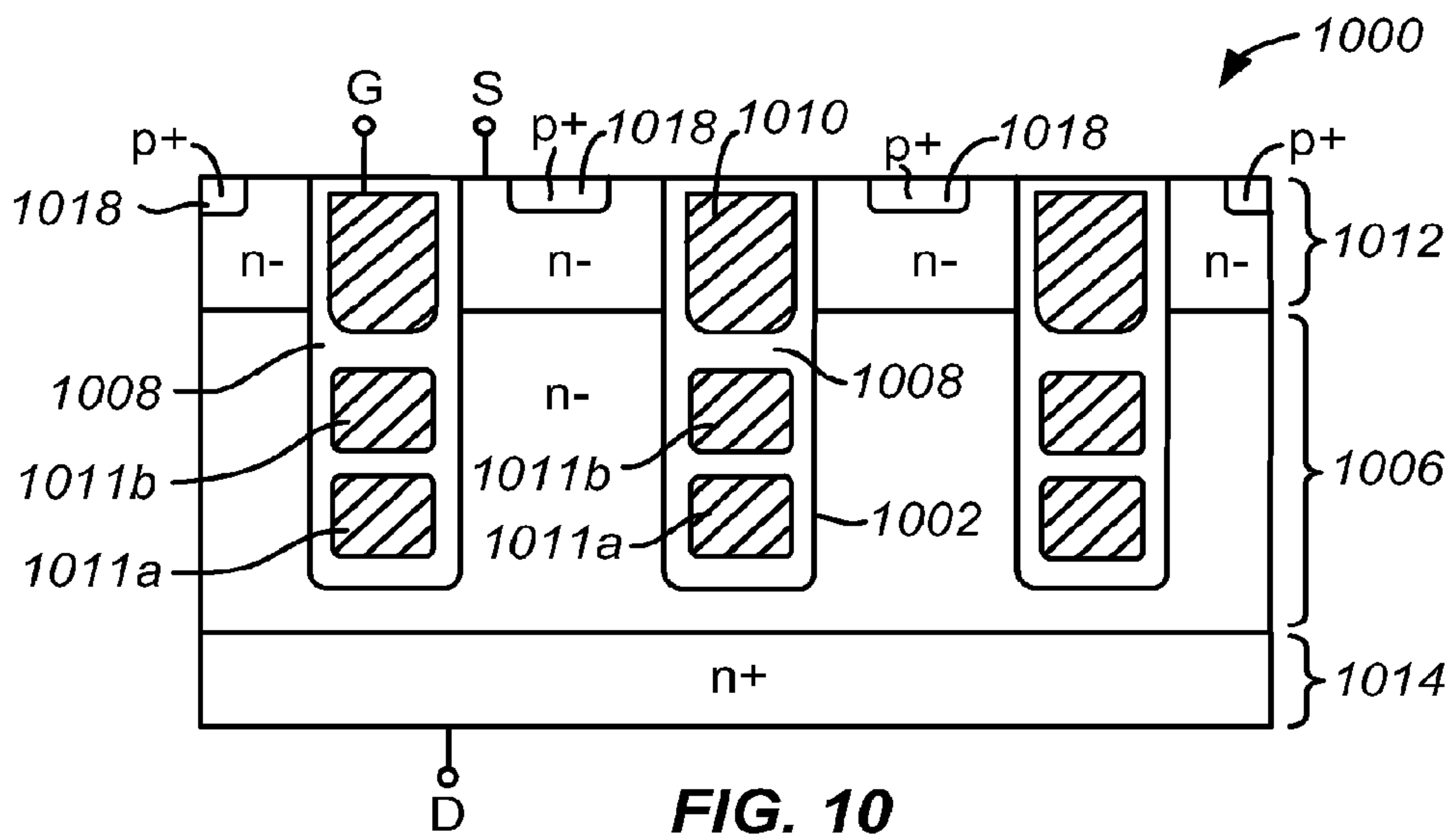
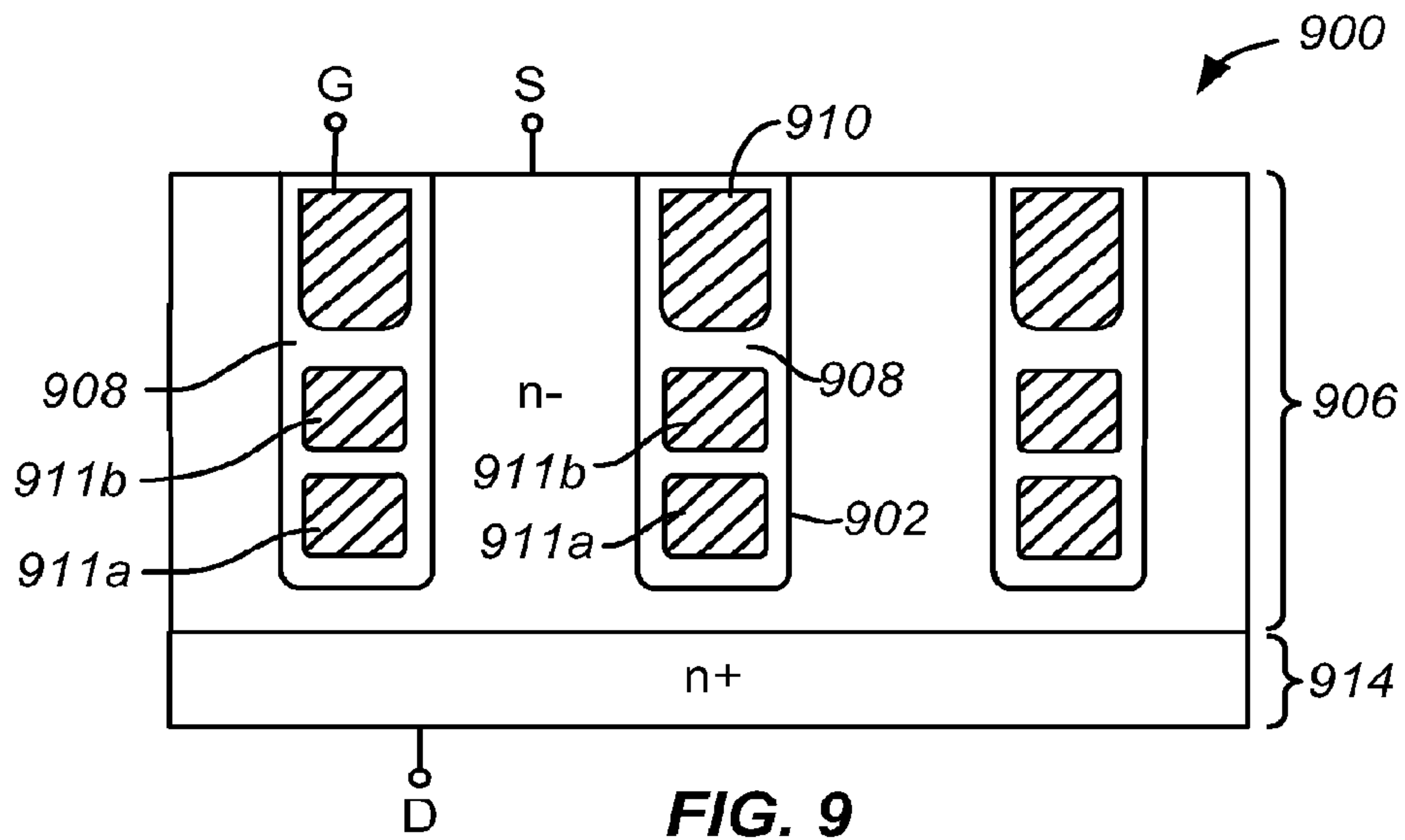
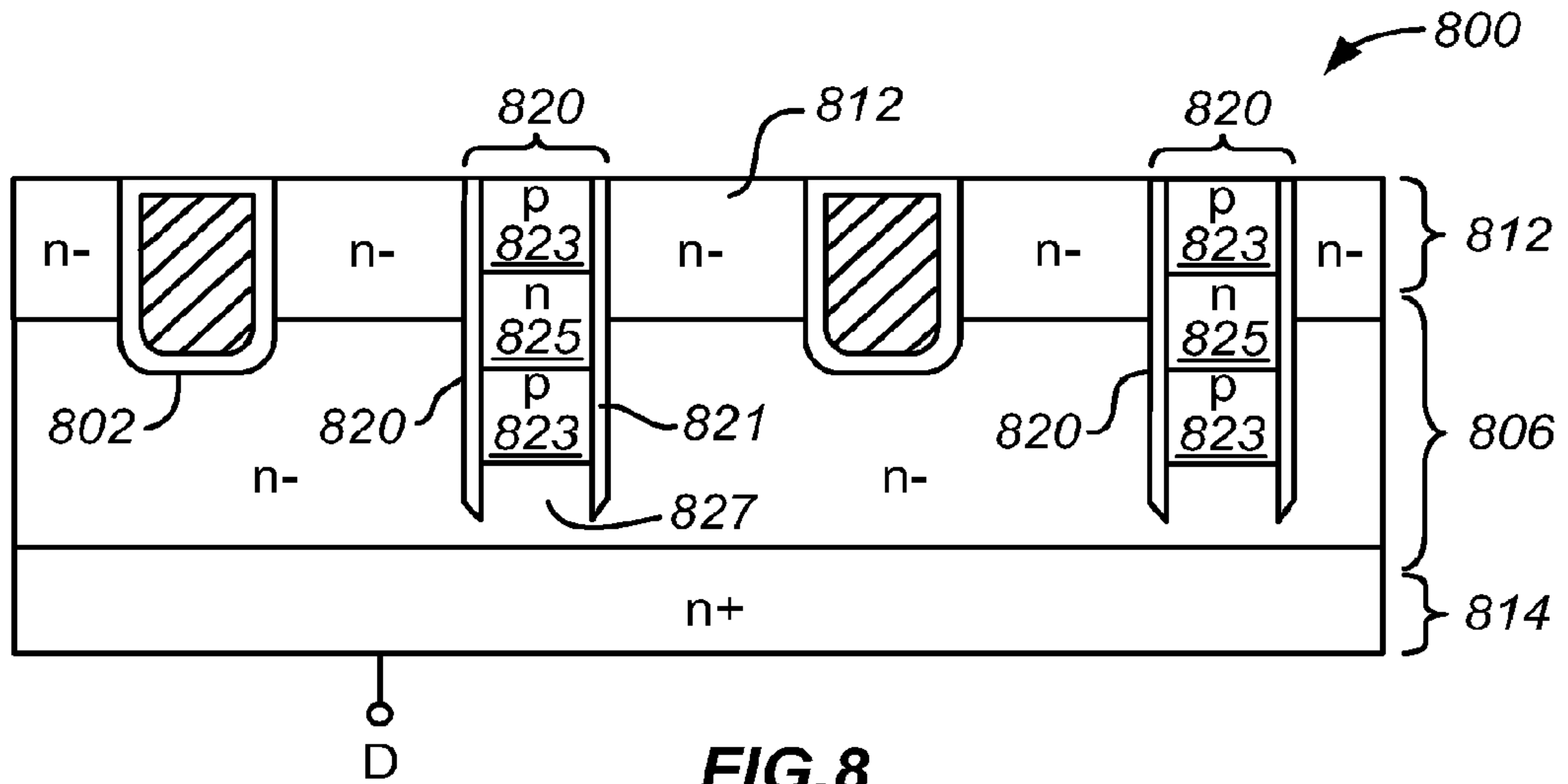


FIG. 7



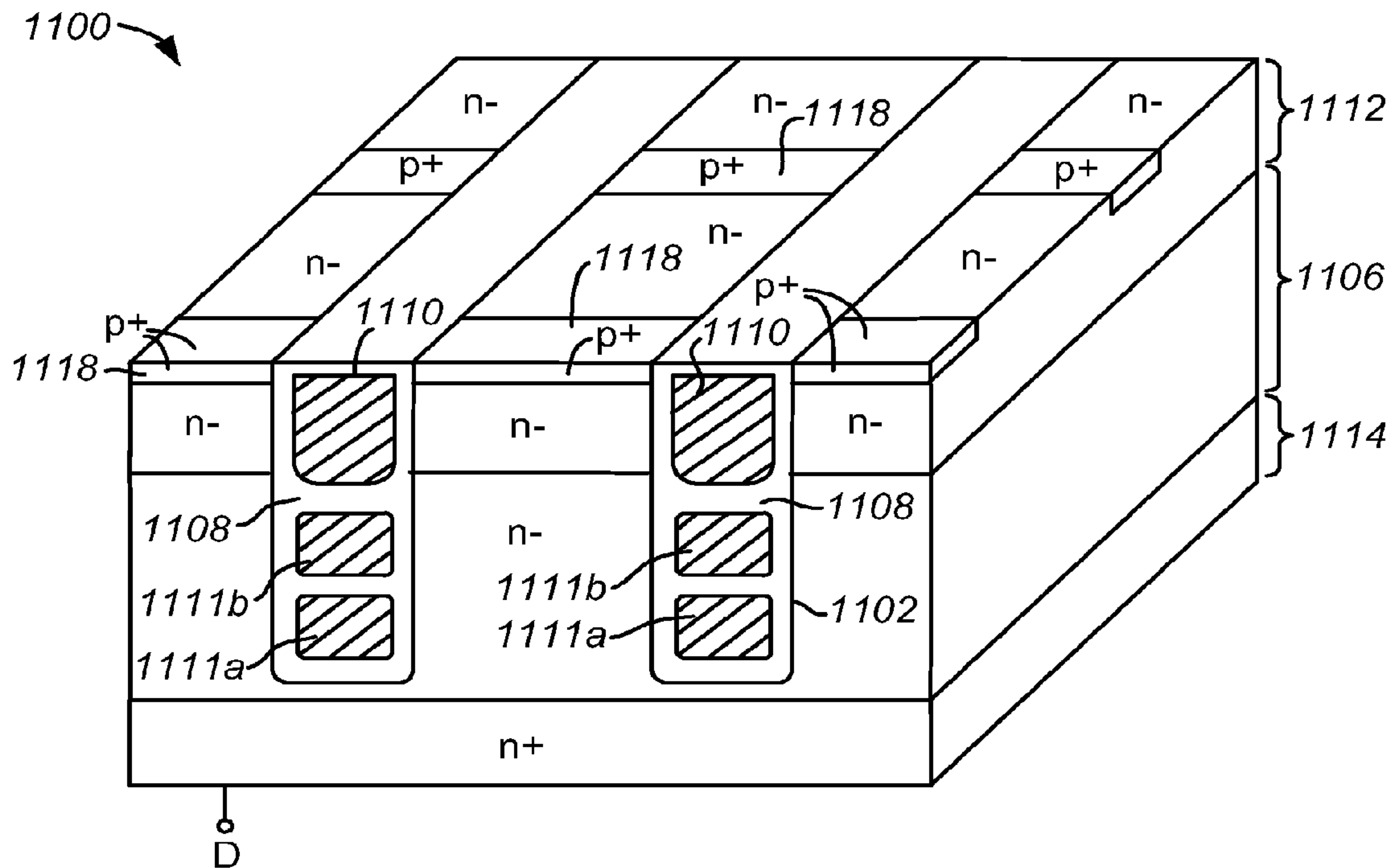


FIG. 11

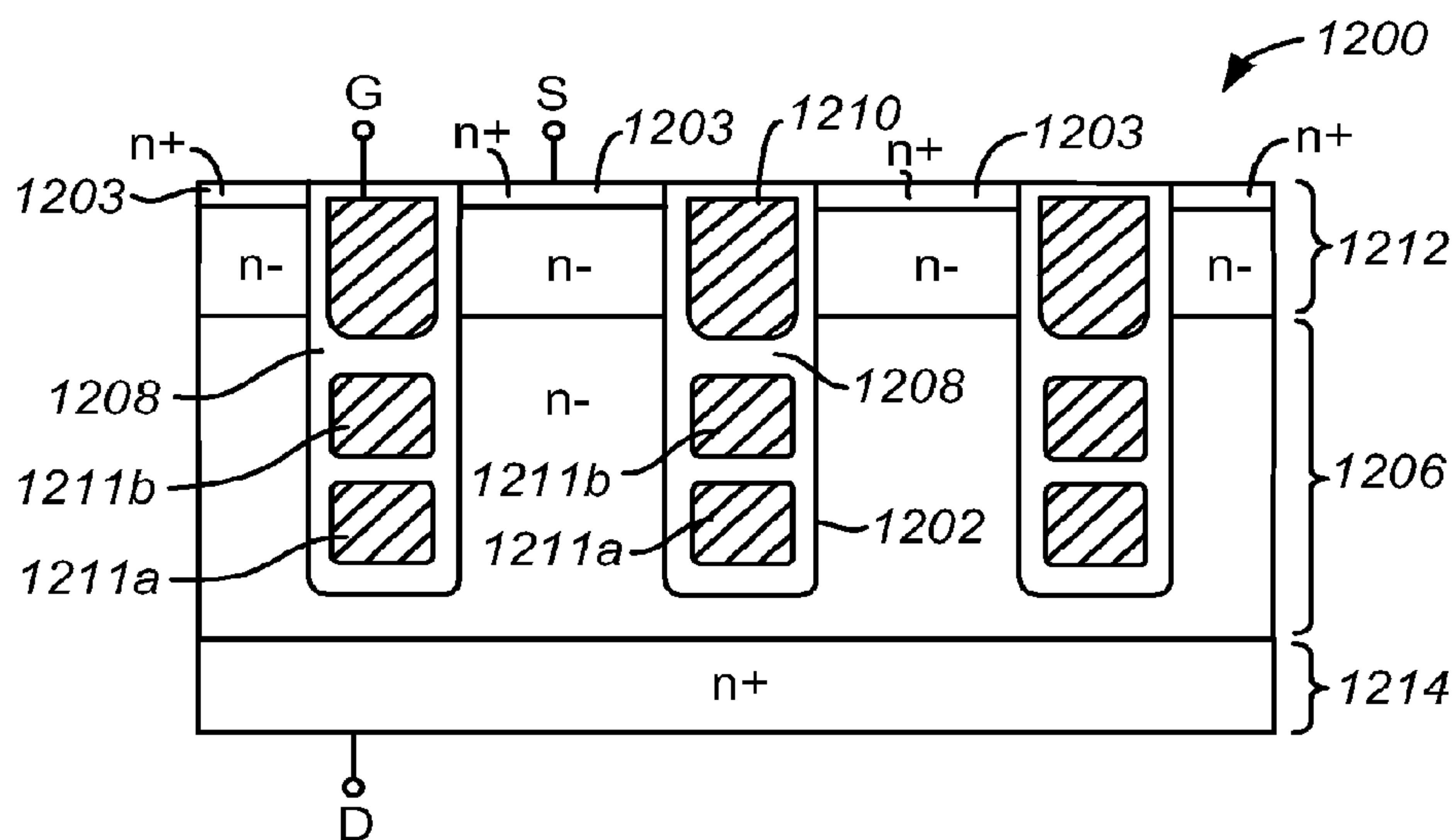


FIG. 12

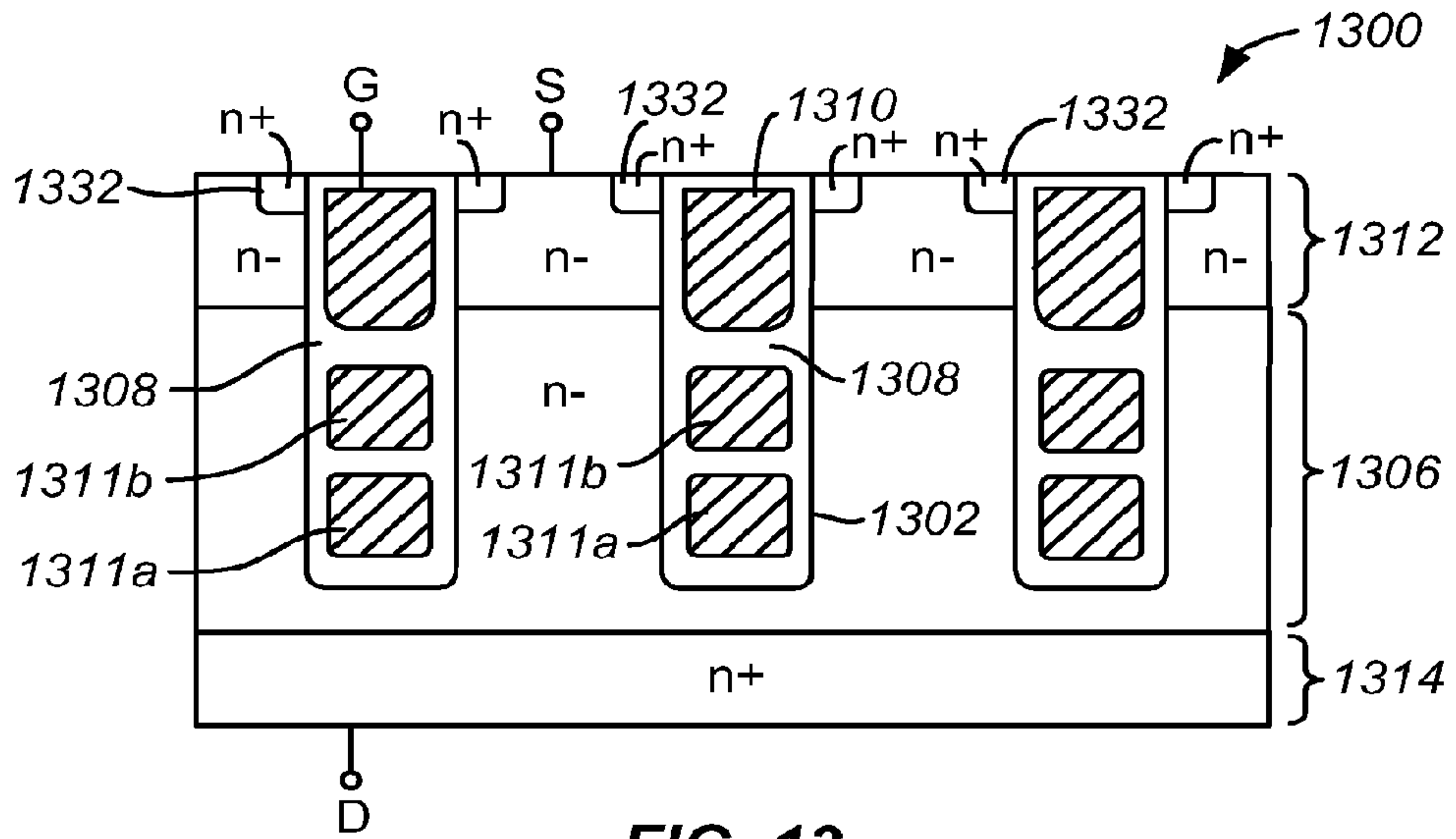


FIG. 13

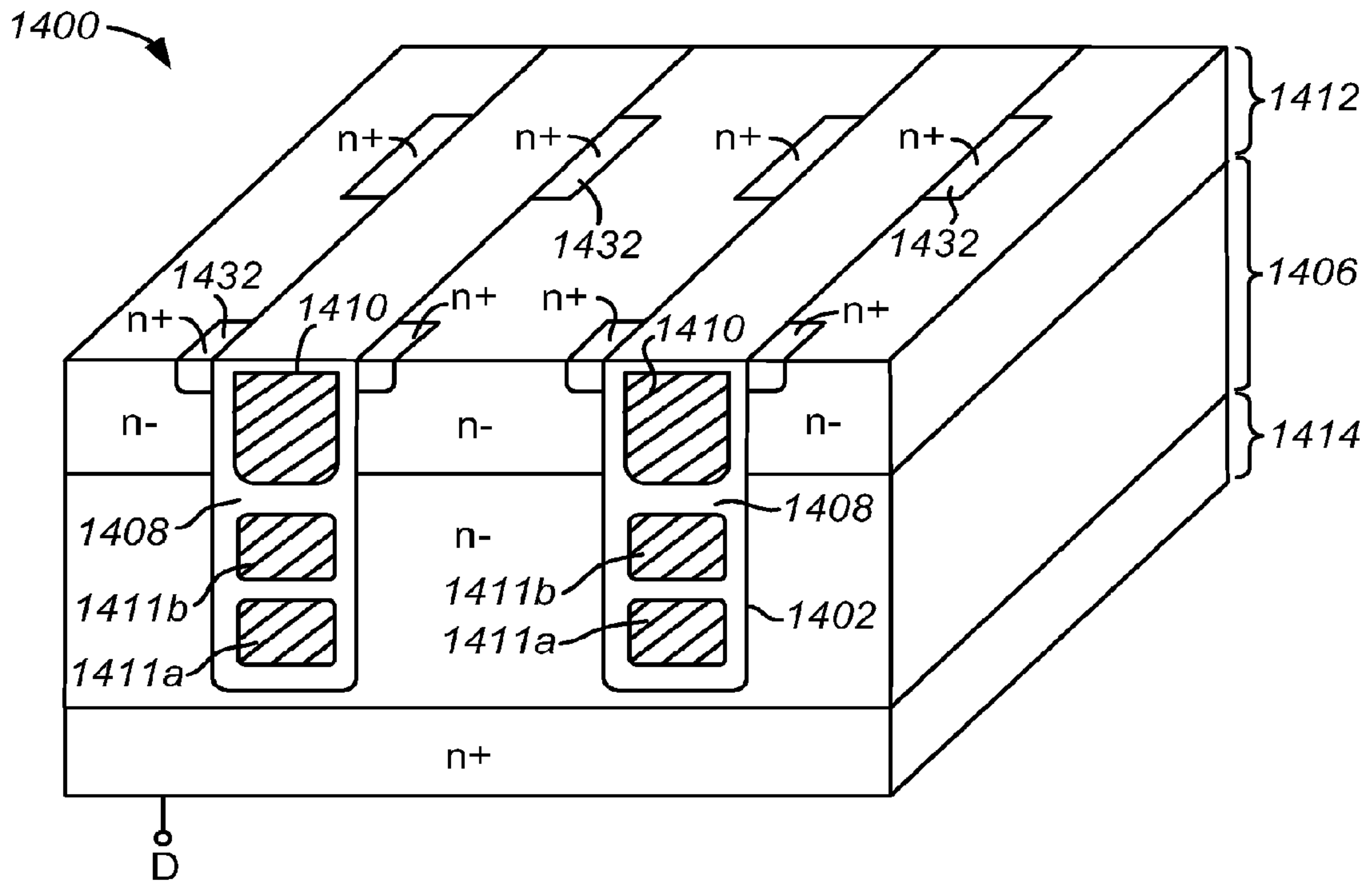


FIG. 14

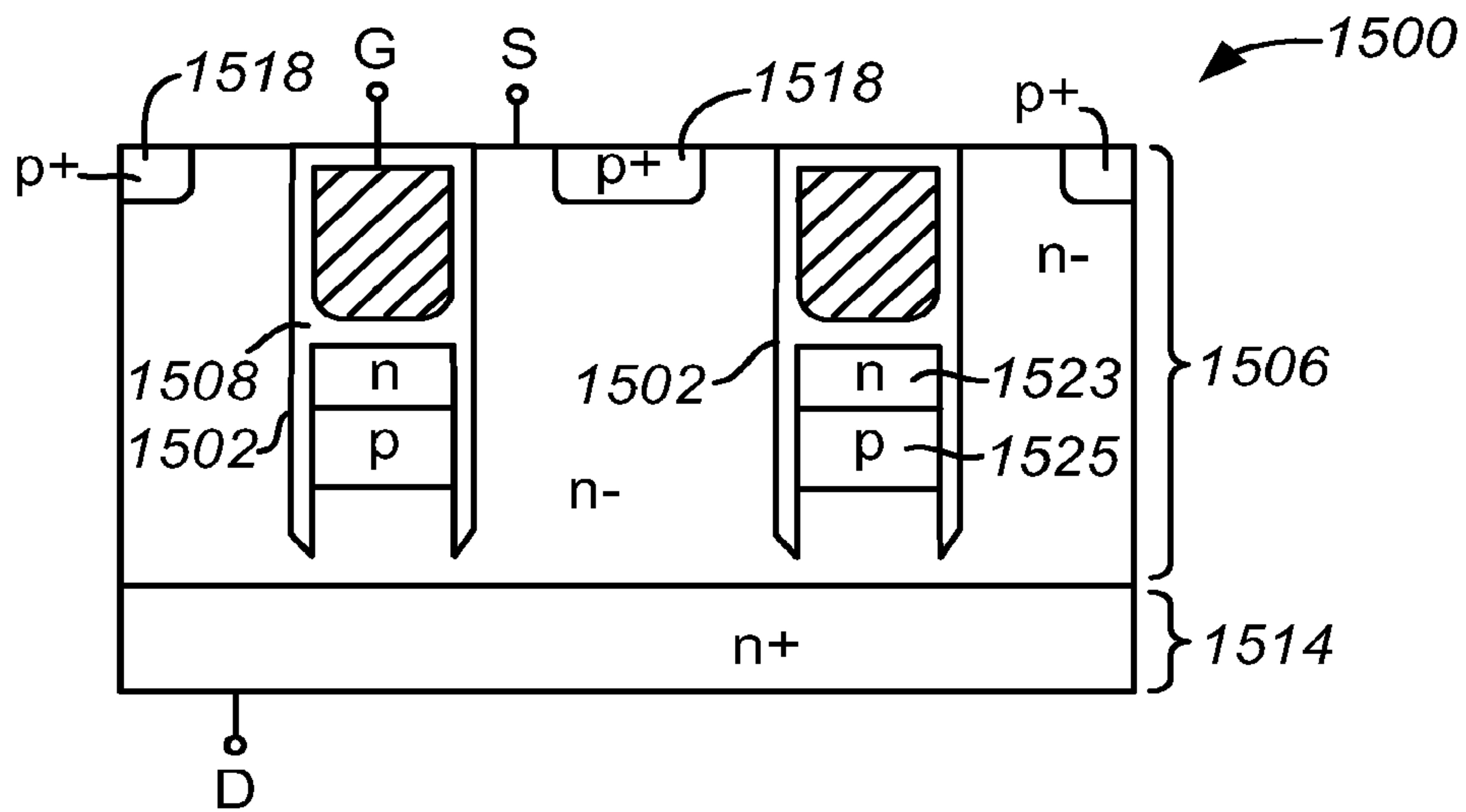


FIG. 15

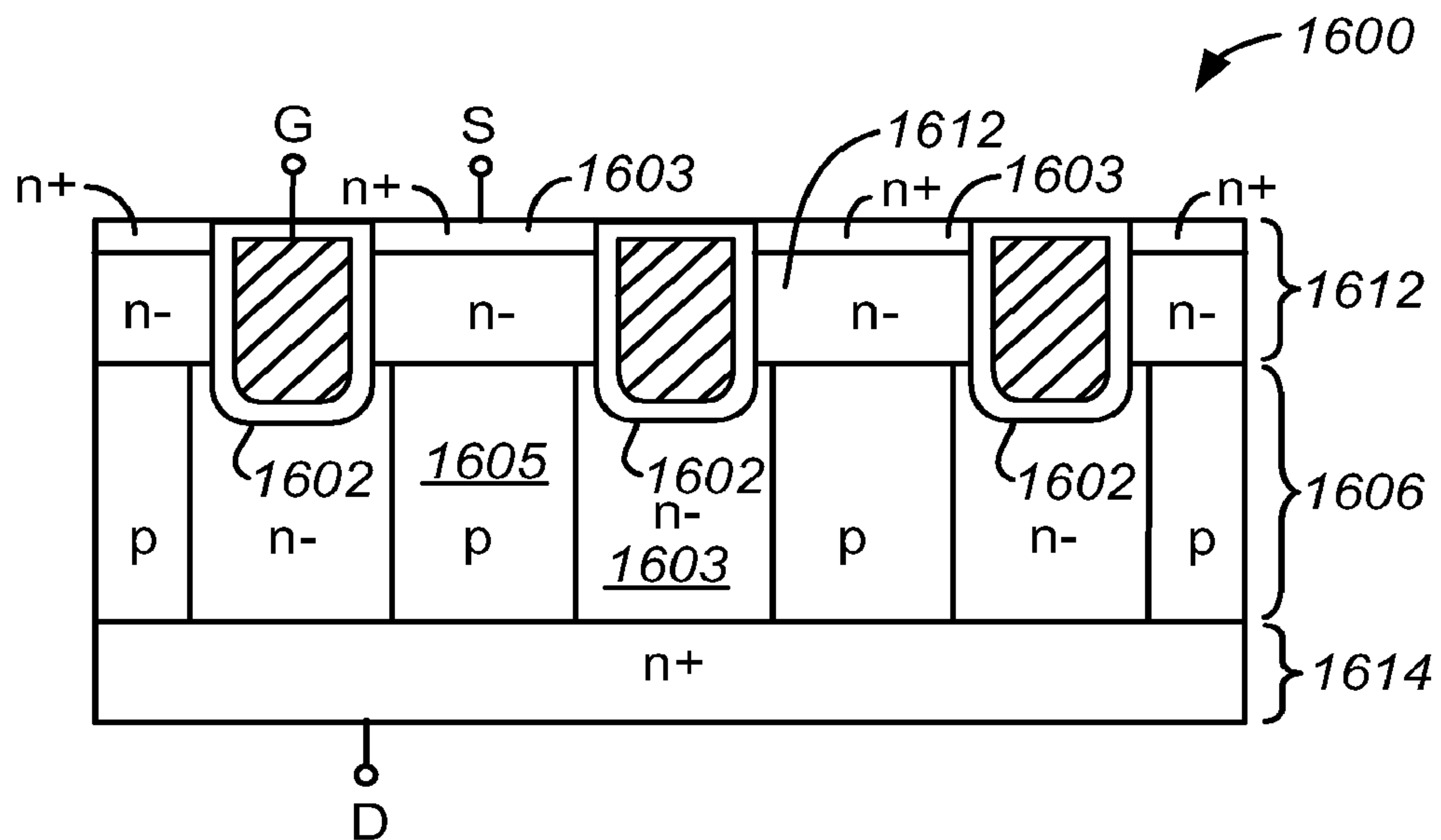


FIG. 16

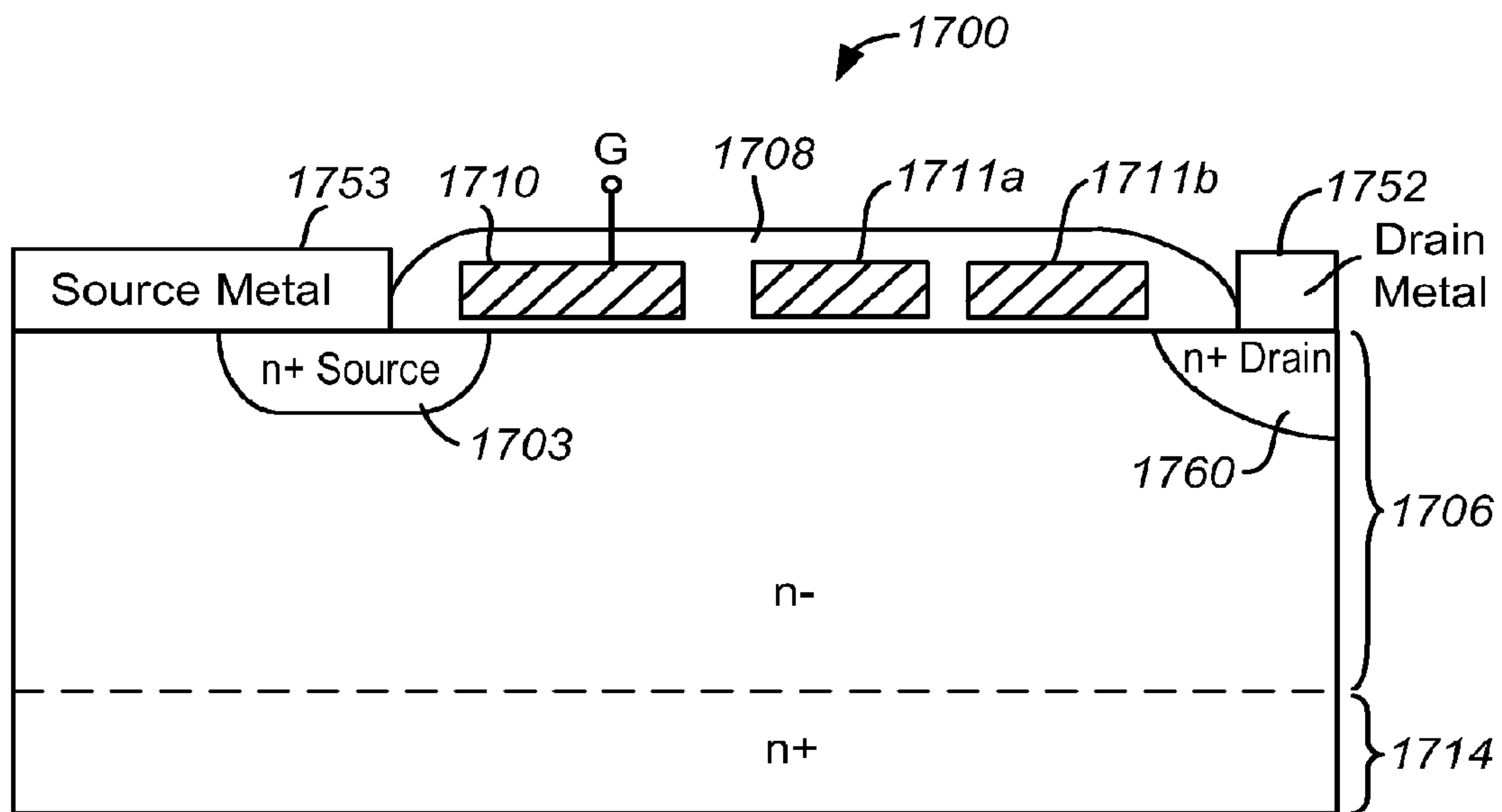


FIG. 17

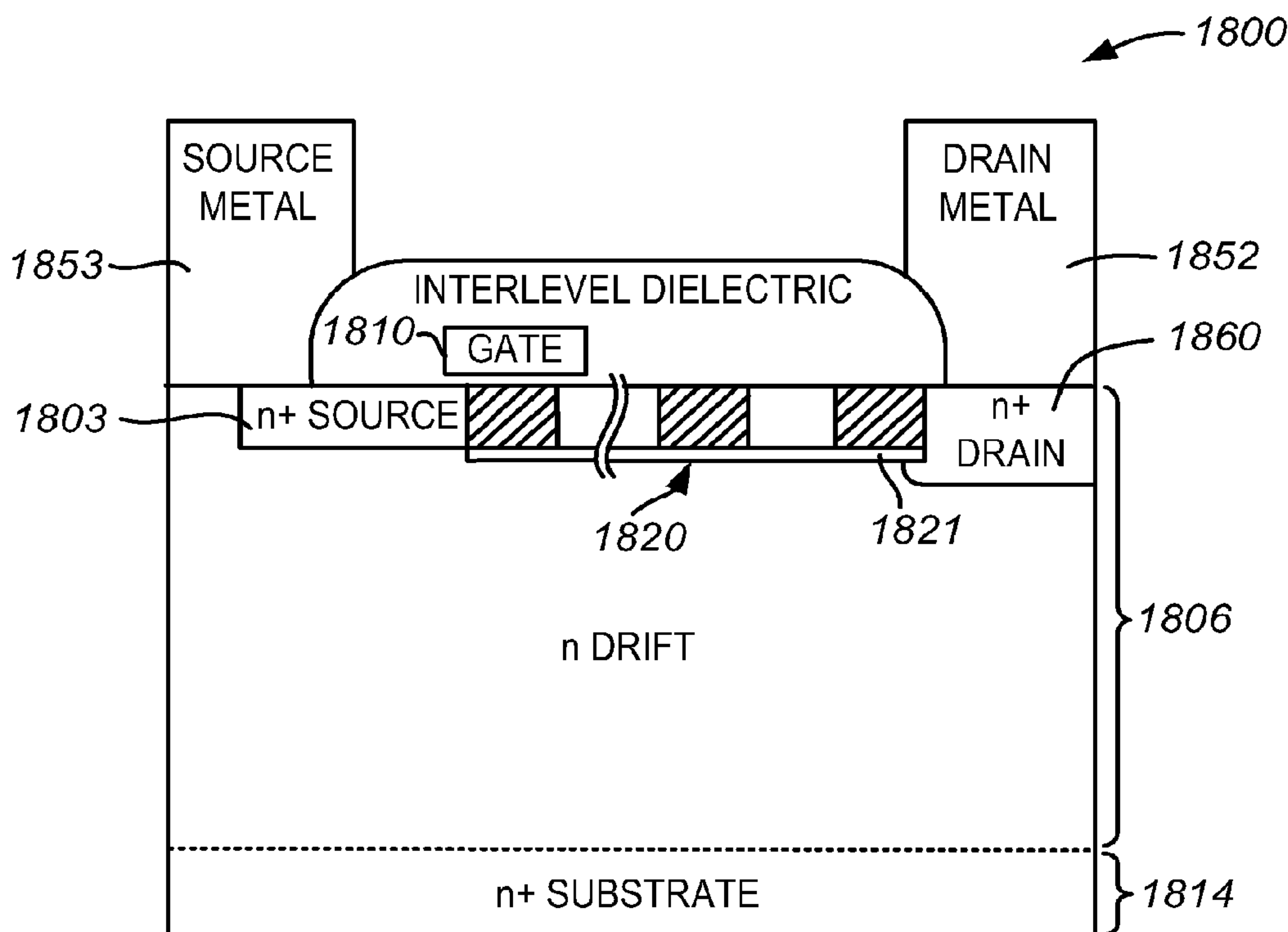


FIG. 18A

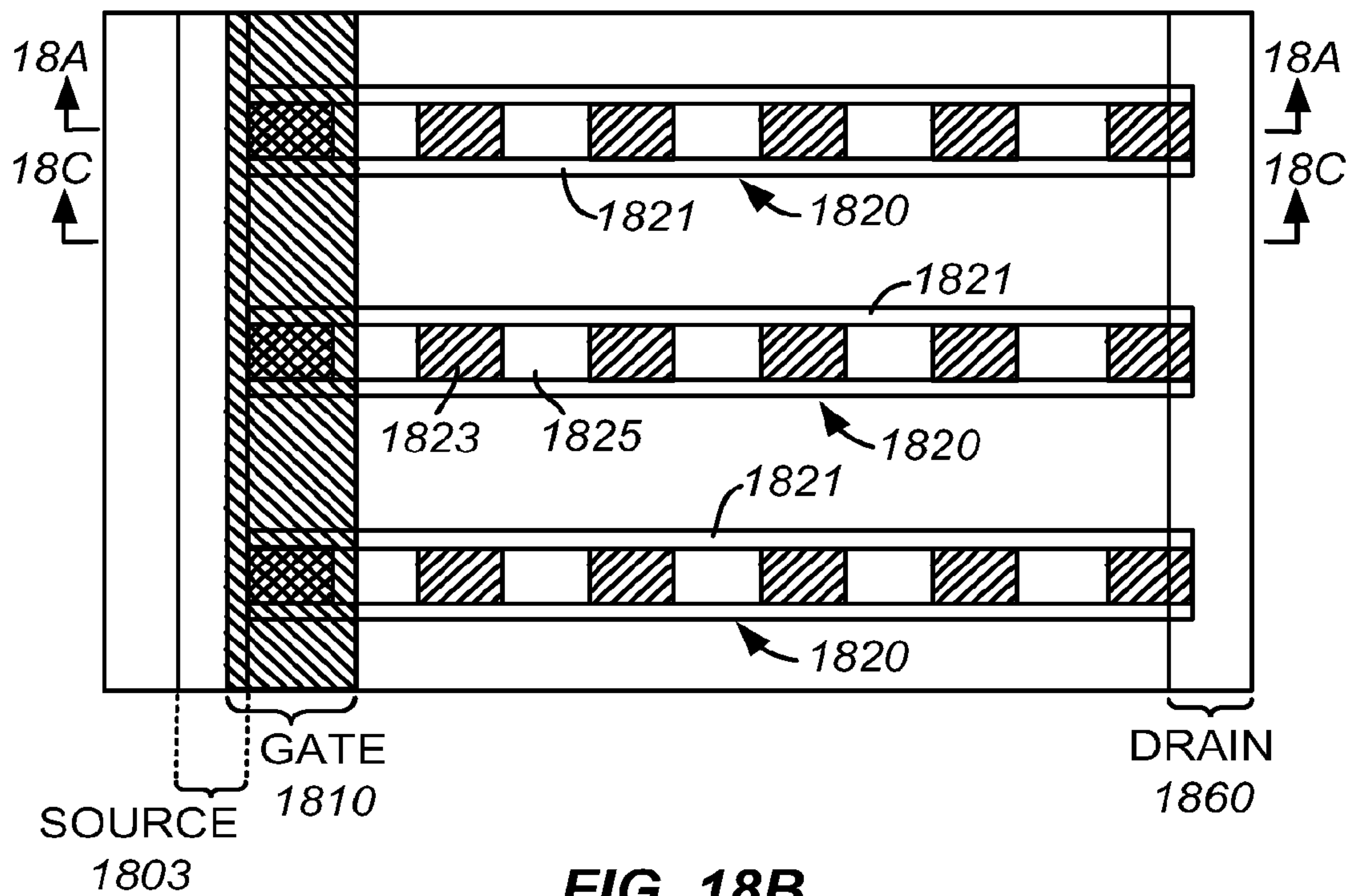


FIG. 18B

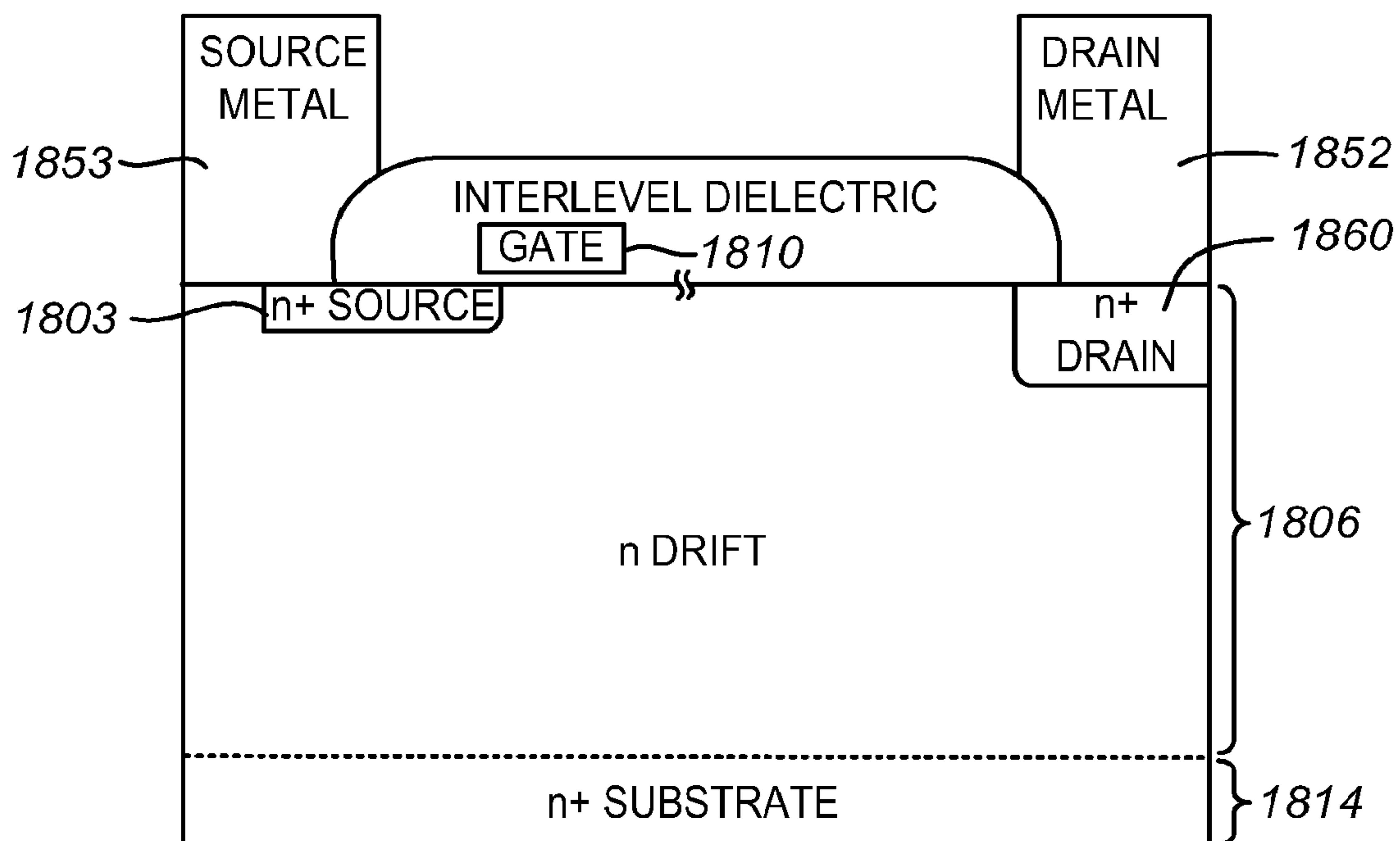


FIG. 18C

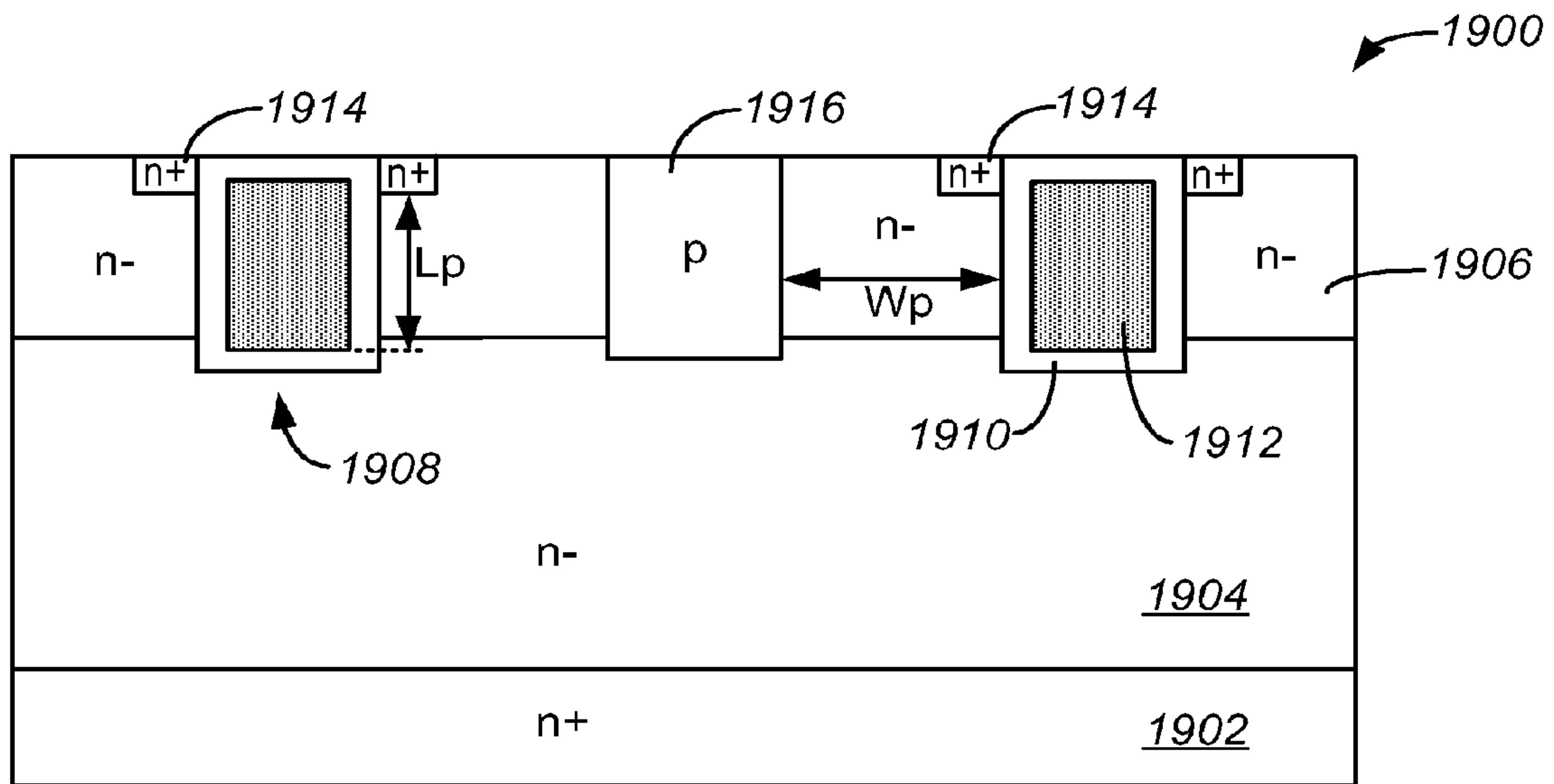


FIG. 19

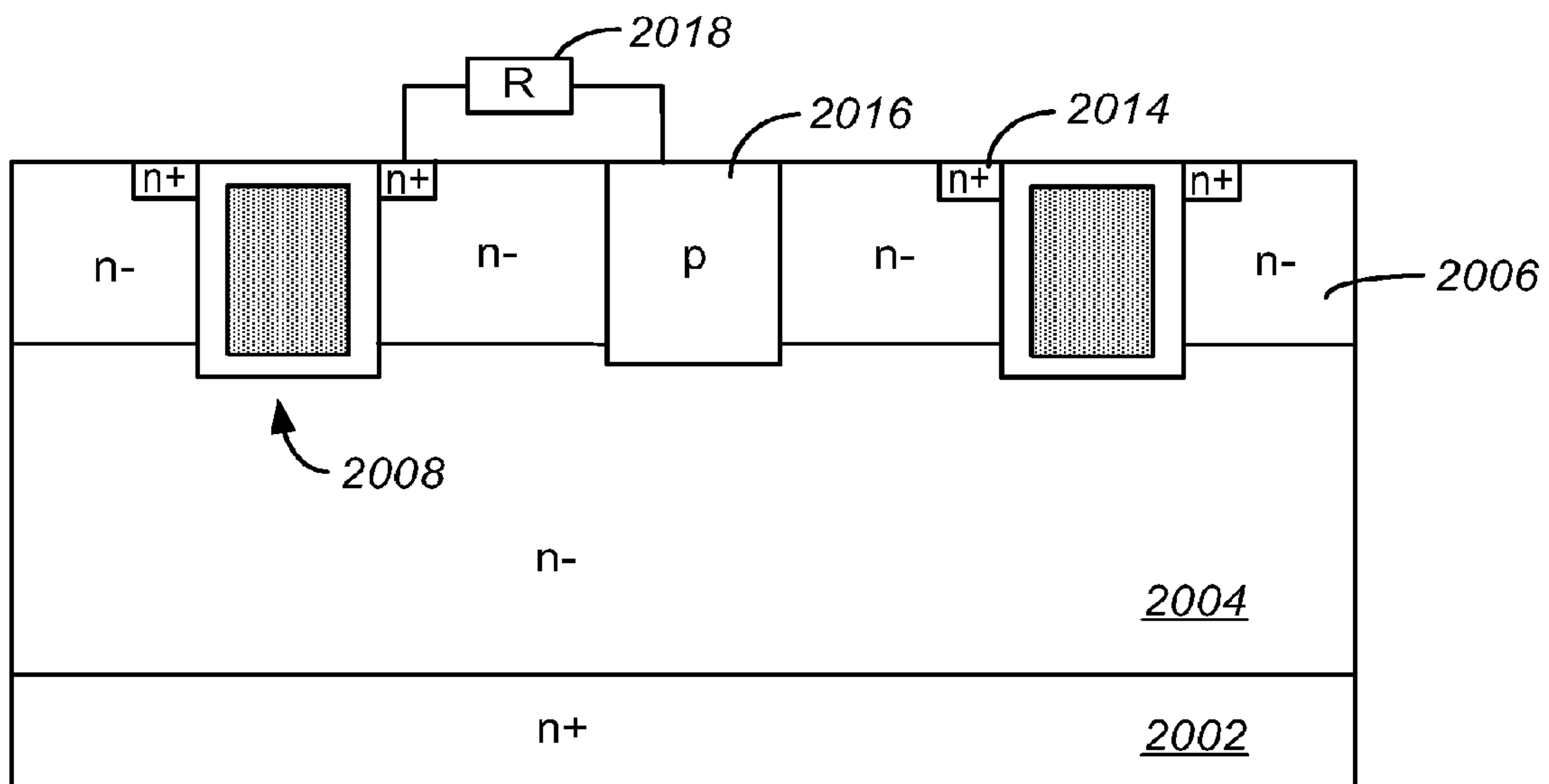


FIG. 20

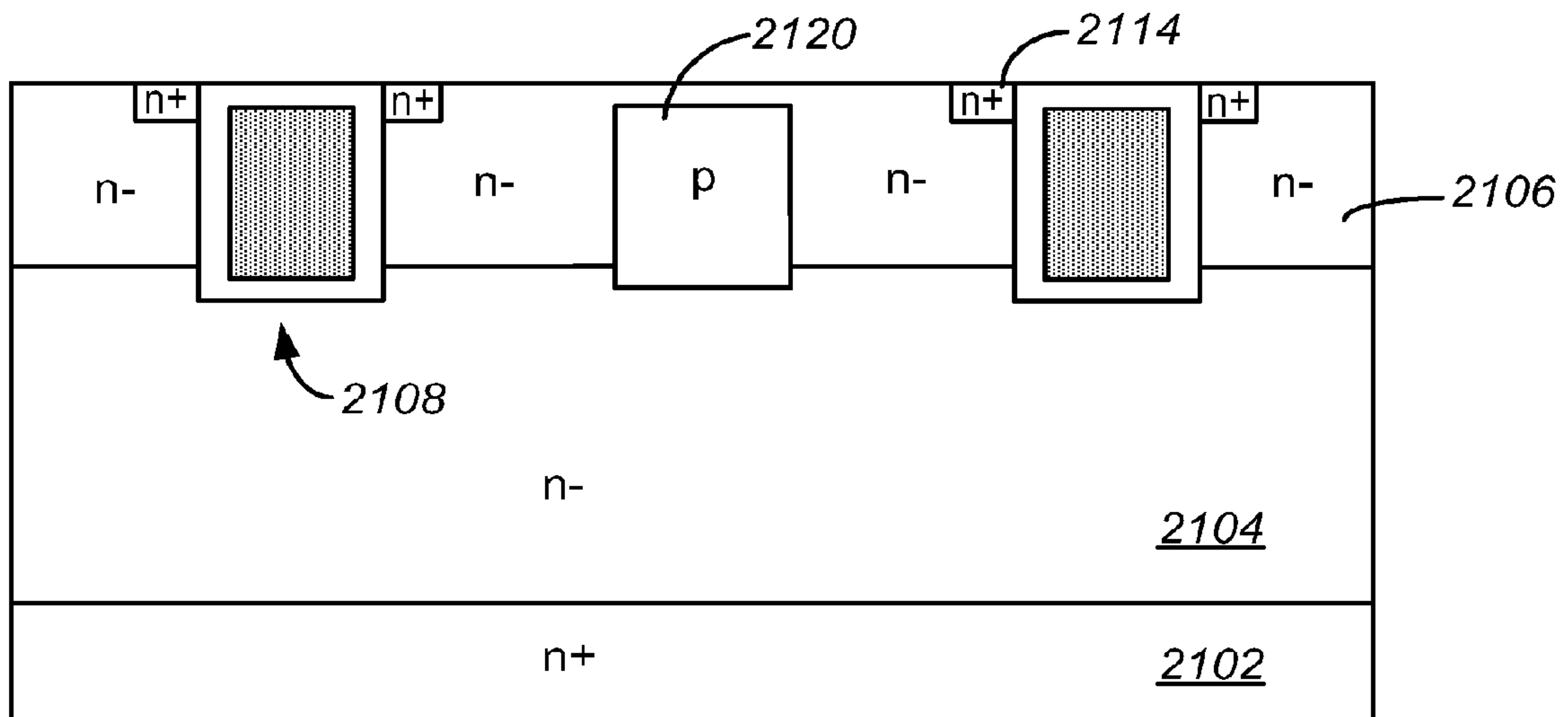


FIG. 21

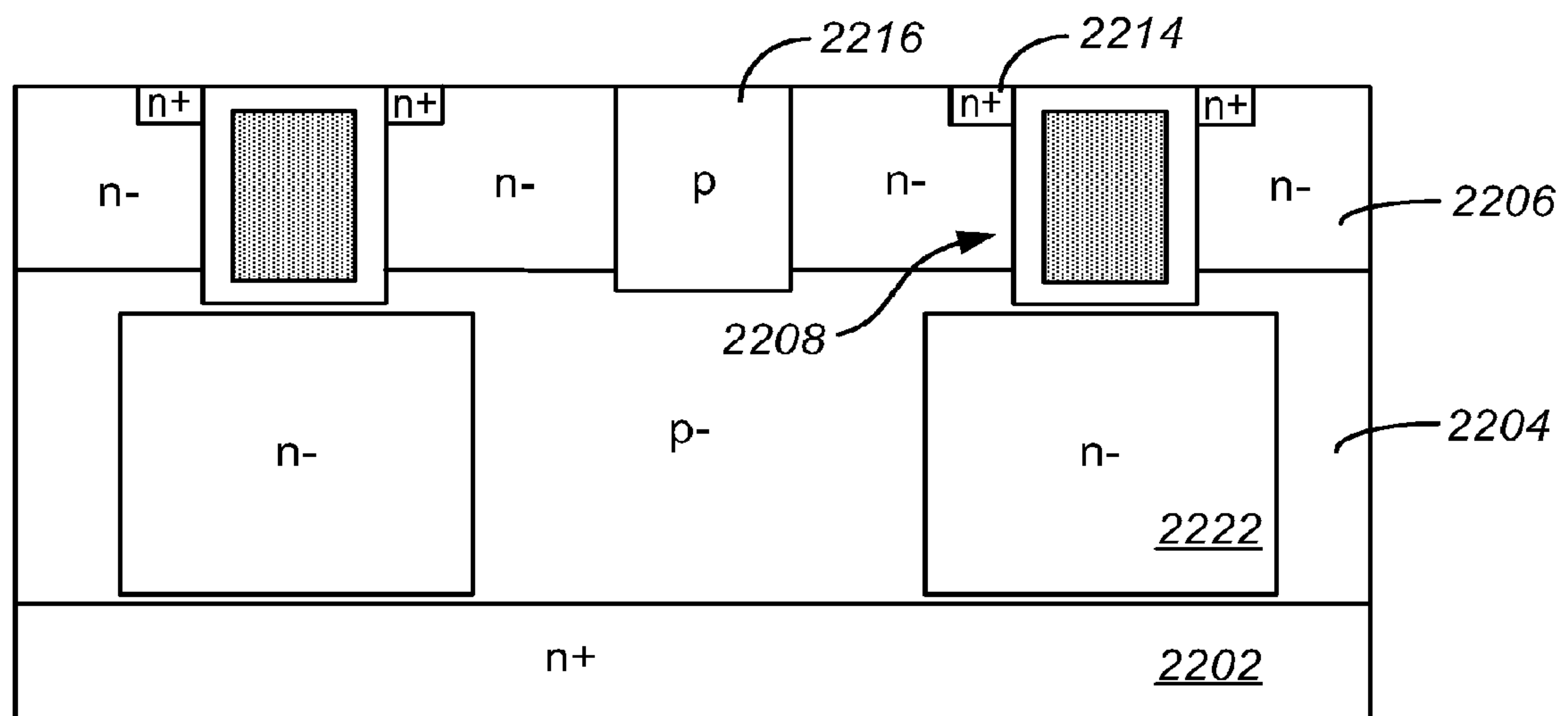


FIG. 22

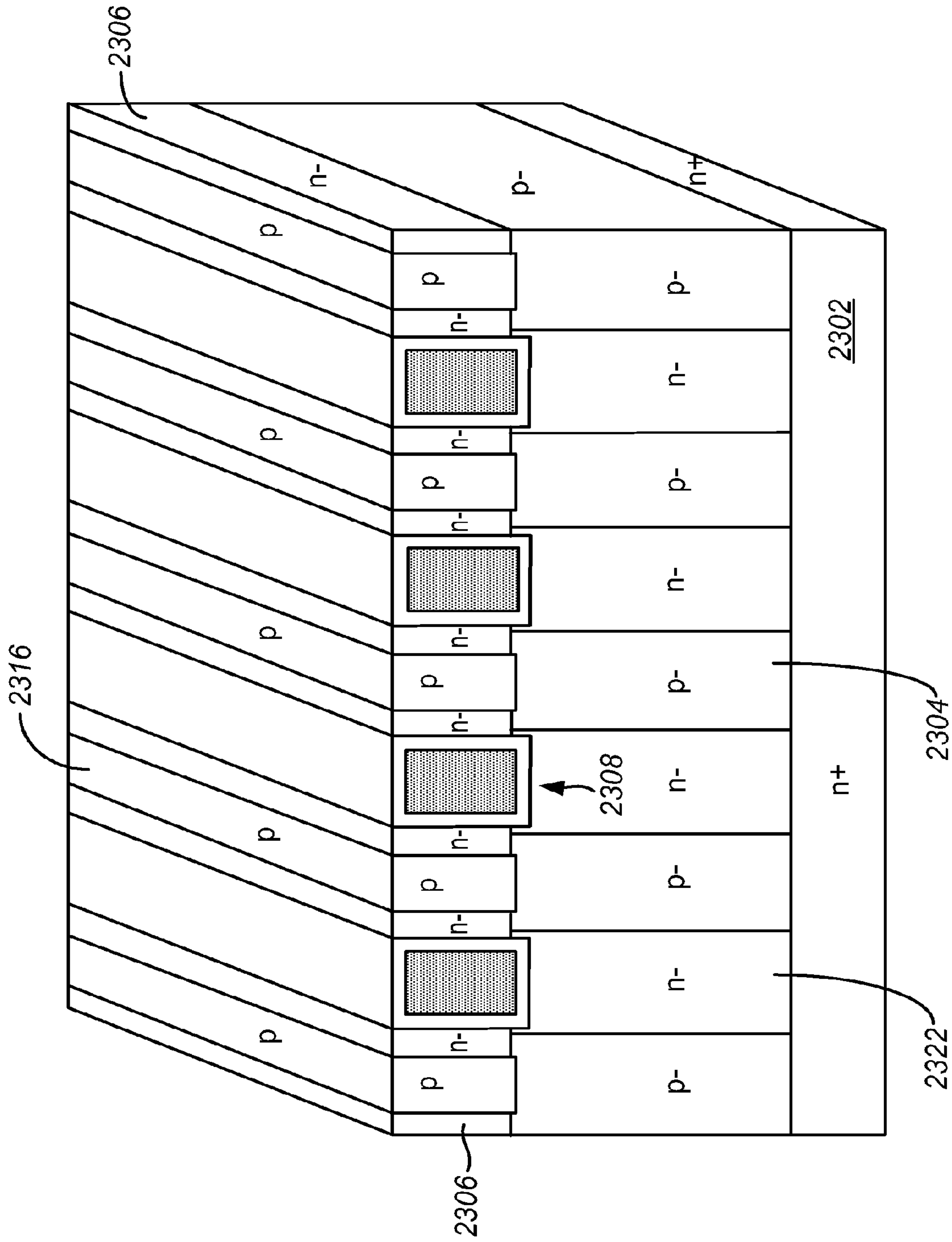


FIG. 23

1

**METHOD FOR FORMING
ACCUMULATION-MODE FIELD EFFECT
TRANSISTOR WITH IMPROVED CURRENT
CAPABILITY**

CROSS-REFERENCE TO RELATED
APPLICATIONS

This is a division of U.S. application Ser. No. 12/114,575, filed May 2, 2008, which is a continuation of U.S. application Ser. No. 11/140,249, filed May 26, 2005, now U.S. Pat. No. 7,368,777, which claims the benefit of U.S. Provisional Application No. 60/588,845, filed Jul. 15, 2004, and U.S. Provisional Application No. 60/669,063, filed Apr. 6, 2005, which are commonly assigned and incorporated herein by reference in their entirety for all purposes. Also, U.S. application Ser. No. 11/140,249 is a continuation-in-part of U.S. patent application Ser. No. 11/026,276, filed Dec. 29, 2004, now U.S. Pat. No. 7,345,342, which is commonly assigned and incorporated herein by reference in its entirety for all purposes.

BACKGROUND

The present invention relates in general to the semiconductor technology and more particularly to semiconductor accumulation-mode power devices with charge balance structures integrated therein.

FIG. 1 shows a cross section view of a conventional trench-gate accumulation-mode vertical MOSFET **100**. MOSFET **100** is an n-channel transistor with a gate terminal formed inside each of trenches **102**, n-type regions **112** between trenches **102** (hereinafter referred to as the channel regions), a drift region **106**, and an n-type drain region **114**. Unlike enhancement-mode transistors, accumulation-mode transistor **100** does not include a blocking (p-type in this example) well or body region inside which the conduction channel is formed. Instead a conducting channel is formed when an accumulation layer is formed in channel regions **112**. Transistor **100** is normally on or off depending on doping concentration of channel regions **112** and doping type of the gate electrodes. It is turned off when channel regions **112** are entirely depleted and lightly inverted. Because no inversion channel is formed, the channel resistance is eliminated thus improving the transistor power handling capability and its efficiency. Further, with no pn body diode, the losses in synchronous rectification circuits attributable to the pn diode are eliminated.

A drawback of accumulation transistor **100** is that drift region **106** needs to be lightly doped to support a high enough reverse bias voltage. However, a lightly doped drift region results in a lower on-resistance and lower efficiency. Thus, there is a need for an accumulation-mode transistor with low on-resistance, high blocking capability, and improved efficiency.

BRIEF SUMMARY

In accordance with an embodiment of the present invention, a method of forming an accumulation-mode field effect transistor includes forming a channel region of a first conductivity type in a semiconductor region of the first conductivity type. The channel region may extend from a top surface of the semiconductor region to a first depth within the semiconductor region. The method also includes forming gate trenches in the semiconductor region. The gate trenches may extend from the top surface of the semiconductor region to a second depth

2

within the semiconductor region below the first depth. The method also includes forming a first plurality of silicon regions of a second conductivity type in the semiconductor region such that the first plurality of silicon regions form P-N junctions with the channel region along vertical walls of the first plurality of silicon regions.

In one embodiment, the first plurality of silicon regions and the gate trenches are alternately arranged so that each of the first plurality of silicon regions is between but laterally spaced from two adjacent gate trenches.

In another embodiment, conduction channels are formed in the channel region along the sidewalls of the gate trenches when the accumulation-mode field effect transistor is in the on state.

In another embodiment, forming the first plurality of silicon regions includes forming body trenches in the semiconductor region, the body trenches extending from the top surface of the semiconductor region to a depth within the semiconductor region below the first depth, and substantially filling the body trenches with silicon material of the second conductivity type. The body trenches and the gate trenches may be alternately arranged so that each body trench is between but laterally spaced from two adjacent gate trenches.

In another embodiment, the first plurality of silicon regions may be formed by implanting dopants of the second conductivity type into the semiconductor region.

In another embodiment, the method also includes forming a gate electrode in each gate trench, the gate electrode being adjacent to but insulated from the channel region.

In another embodiment, the semiconductor region includes an epitaxial layer extending over and in contact with a substrate. The substrate and the epitaxial layer may be the first conductivity type, and the epitaxial layer may have a lower doping concentration than the substrate. The channel region, the trenches and the first plurality of silicon regions may extend into the epitaxial layer.

In another embodiment, the method may also include forming a second plurality of silicon regions of the first conductivity type in the channel region such that each pair of the second plurality of silicon regions flanks sides of a corresponding one of the gate trenches.

The second plurality of silicon regions may have a higher doping concentration than that of the channel region. The method may also include forming a resistor coupled between the first plurality of silicon regions and the second plurality of silicon regions.

In another embodiment, the gate trenches and the first plurality of silicon regions are parallel-extending continuous stripes.

In another embodiment, the first plurality of silicon regions are formed in the semiconductor region such that an uppermost surface of each of the first plurality of silicon regions is below the top surface of the semiconductor region.

In yet another embodiment, the method may also include forming columns of silicon of the second conductivity type in the semiconductor region so that the columns of silicon of the second conductivity type and the semiconductor region together form alternating columns of first and second conductivity type silicon. No current may flow through the columns of silicon of the second conductivity type when the accumulation-mode field effect transistor is in the on state.

In still another embodiment, each of the columns of silicon of the second conductivity type extend directly below a corresponding one of the plurality of first silicon regions.

These and other embodiments of the invention will be described with reference to the accompanying drawings and following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a cross section view of a conventional
trenched-gate accumulation-mode vertical field effect trans-
istor;

FIG. 2 shows a cross section view of an exemplary
trenched-gate accumulation-mode vertical field effect trans-
istor with alternate conductivity type regions in accordance
with an embodiment of the invention;

FIGS. 3 and 4 show cross section views of two exemplary
trenched-gate accumulation-mode vertical field effect trans-
istors with trenched electrodes in accordance with other
embodiments of the invention;

FIGS. 5 and 6 are cross section views of two exemplary
trenched-gate accumulation-mode vertical field effect trans-
istors with dielectric-filled trenches in accordance with other
embodiments of the invention;

FIGS. 7 and 8 show cross section views of two exemplary
trenched-gate accumulation-mode vertical field effect trans-
istors with trenched diodes in accordance with other
embodiments of the invention;

FIG. 9 shows a cross section view of a variation of the FIG.
3 embodiment wherein the channel regions and the drift
region are merged (i.e., have the same doping concentration)
in accordance with another embodiment of the invention;

FIGS. 10 and 11 show cross section views of two variations
of the FIG. 3 embodiment wherein heavily doped opposite
conductivity-type regions are formed in the channel regions
in accordance with other embodiments of the invention;

FIGS. 12 and 13 show cross section views of two variations
of the FIG. 3 embodiment wherein heavily doped same con-
ductivity-type regions are formed in the channel regions in
accordance with other embodiments of the invention;

FIG. 14 shows a three dimensional view of the FIG. 13
embodiment;

FIG. 15 shows a cross section view of a variation of the
FIG. 7 embodiment wherein the channel regions are merged
with the drift region (i.e., have the same doping concentra-
tion), and heavily doped opposite conductivity-type regions
are formed in the channel regions in accordance with another
embodiment of the invention;

FIG. 16 shows a cross section view of a variation of the
FIG. 2 embodiment wherein heavily doped same conductiv-
ity-type regions are formed in the channel regions in accor-
dance with another embodiment of the invention;

FIG. 17 shows a cross section view of an exemplary planar-
gate accumulation-mode lateral field effect transistor with
charge balancing electrodes in accordance with another
embodiment of the invention;

FIG. 18A shows a cross section view of an exemplary
planar-gate accumulation-mode lateral field effect transistor
with trenched diodes in accordance with another embodiment
of the invention;

FIG. 18B shows a top layout view of the embodiment
shown in FIG. 18A;

FIG. 18C shows a cross section view along 18C-18C line in
FIG. 18B;

FIG. 19 shows a cross-section view of a trenched-gate
accumulation FET in accordance with an embodiment of the
present invention;

FIG. 20 shows a variation of the FIG. 19 FET wherein a
resistor 2718 is coupled between the body and source regions;

FIG. 21 show yet another variation of the FIG. 19 FET
wherein the body regions are buried in silicon;

FIG. 22 shows an exemplary implementation of the FIG.
19 FET in a multi-pillar charge balance structure; and

FIG. 23 shows an isometric view of a FET with charge
balance structure wherein continuous stripes of body regions
are used, in accordance with another embodiment of the
invention.

DETAILED DESCRIPTION

In accordance with the present invention, charge spreading
techniques are advantageously integrated in vertical and lat-
eral accumulation-mode power devices to achieve lower on-
resistance, higher blocking capability and improved effi-
ciency.

FIG. 2 shows a simplified cross section view of an exem-
plary accumulation-mode field effect transistor 200 with
alternate conductivity regions 203, 205 extending vertically
parallel to the current flow. In this example, transistor 200
is an n-channel transistor with a gate terminal formed inside
each of trenches 202, n-type channel regions 212 between
trenches 202, a drift region 206 that includes opposite polarity
columnar n-type and p-type sections 203 and 205, and an
n-type drain region 214. Unlike enhancement-mode transis-
tors, accumulation-mode transistor 200 does not include a
blocking (p-type in this example) well or body region inside
which the conduction channel is formed. Instead a conducting
channel is formed when an accumulation layer is formed in
channel regions 212. Transistor 200 is normally on or off
depending on doping concentration of channel regions 212
and doping type of the gate electrodes. It is turned off when
channel regions 212 are entirely depleted and lightly inverted.

In the embodiments describe herein, those portions of the
drift region through which current flows when the transistor is
in an on state are referred to as the conduction regions.

The doping concentrations in opposite polarity regions 203
and 205 are adjusted to maximize charge spreading, which
enables the transistor to support higher voltages and also
results in more efficient use of the silicon. The use of colum-
nar opposite polarity regions parallel to the current flow flat-
tens the electric field distribution in the conduction regions by
not allowing it to decrease linearly away from the junction
formed between regions 212 and 206. The charge spreading
effect of this structure allows the use of a more highly doped
drift region 206 which advantageously reduces transistor on-
resistance. The doping concentration of the various regions
may vary; for example, n-type regions 212 and 203 may have
the same or different doping concentrations. The embodiment
wherein n-type regions 212 and 203 have the same doping
concentration is simpler to manufacture and thus less costly,
and is attractive for use in low voltage applications. Those
skilled in the art appreciate that an improved p-channel tran-
sistor can be obtained by reversing the polarities of the vari-
ous regions of the transistor shown in FIG. 2.

An exemplary method of forming the accumulation-mode
transistor in FIG. 2 is as follows. An n-type epitaxial layer is
formed over substrate 214 in accordance with conventional
methods. Using a masking layer, columns of silicon are
removed from the epitaxial layer using conventional silicon
etching techniques. Silicon material 205 of p-type conductiv-
ity is then formed in the removed columns of silicon using
known techniques. An n-type epitaxial layer 212 is then
formed over epitaxial layer 206 using conventional tech-
niques. Trenched gate structures are then formed in epitaxial
layer 212 using known methods.

FIG. 3 is a simplified cross section view of another accu-
mulation-mode field effect transistor 300 with trenched elec-
trodes for charge spreading purposes. Channel regions 312,
drift region 306 and drain region 314 are all of the same
conductivity type which in this example is n-type. The doping

concentration of channel regions **312** is adjusted to form a depleted blocking junction under no bias conditions. Inside each trench **302**, one or more buried electrodes **311** are formed under gate electrode **310**, all insulated from one another and from drift region **306** by dielectric material **308**. Buried electrodes **311** act as field plates and can be biased, if desired, to a potential that optimizes their charge spreading effect. Since charge spreading can be controlled by independently biasing buried electrodes **311**, the maximum electric field can be increased significantly. Different variations of this structure are possible. For example, the depth of trench **302** and the size and number of buried electrodes **311** can vary depending on the application. Charge spreading electrodes can be buried inside trenches that are separate from active trenches that house the transistor gate electrode. An example of such an embodiment is shown in FIG. 4.

A method of forming the structure in FIG. 3 is as follows. An n-type epitaxial layer is formed over substrate **314**. An n-type layer **312** is formed along an upper portion of the epitaxial layer by implanting dopants into the epitaxial layer. Depending on the desired doping concentration, n-type dopants may be implanted into the epitaxial layer so that n-type layer **312** has a higher doping concentration than drift region **306** of the epitaxial layer, or alternatively, p-type counter-dopants may be implanted into the epitaxial layer so that n-type layer **312** has a lower doping concentration than drift region **306** of the epitaxial layer. In another embodiment, regions **306** and **312** are formed by growing two n-type epitaxial layers having different doping concentrations. An exemplary set of process steps for forming the trenched electrodes are described in the above-referenced commonly assigned U.S. patent application Ser. No. 10/821,796 titled "Schottky Diode Using Charge Balance Structure," filed Apr. 9, 2004, incorporated herein by reference in its entirety. The trenched-gate structures are formed using conventional techniques.

Another embodiment for an improved accumulation-mode transistor employs dielectric-filled trenches with an opposite polarity exterior liner. FIG. 5 is a simplified cross section view of an accumulation transistor **500** according to this embodiment. Dielectric-filled trenches **520** extend downward from the surface of the silicon well into drift region **506**. Trenches **520** are substantially filled with dielectric material such as silicon dioxide. In this exemplary embodiment, transistor **500** is an n-channel transistor with trenched-gate structure. A p-type region **526** lines the exterior sidewalls and bottom of dielectric-filled trenches **520** as shown. Dielectric-filled trenches **520** reduce the output capacitance of the transistor while p-type liner **526** provides for charge balancing in the drift region to increase the blocking capability of the transistor. In one exemplary method of forming transistor **500**, regions **506** and **512** are formed in a similar manner to previous embodiments. A set of process steps for forming the dielectric-filled trenches is disclosed in the above-referenced commonly assigned U.S. Pat. No. 6,376,878 to Christopher B. Kocon, titled "MOS-Gated Devices with Alternating Zones of Conductivity," incorporated herein in its entirety. The trenched-gate structures are formed using conventional techniques.

In an alternative embodiment shown in FIG. 6, oppositely doped liners **626N** and **626P** are formed adjacent the opposite sidewalls of a dielectric-filled trench **620**. That is, a dielectric-filled trench **620** has a p-type liner **626P** extending along the exterior sidewall on one side, and an n-type liner **626N** extending along the exterior sidewall on the opposite side of the same trench. Other variations of this accumulation transistor with dielectric-filled trenches are possible. These

include, for example, an accumulation transistor with a planar (as opposed to trenched) gate structure; an accumulation transistor with a p-type liner that covers only the exterior sidewalls and not the bottom of trenches **526**; and an accumulation transistor with a single trench structure with a p-type liner that lines the lower portion of the trench.

In another embodiment, an accumulation-mode transistor employs one or more diodes stacked inside a trench for charge balancing purposes. A simplified cross section view of an exemplary accumulation-mode transistor **700** according to this embodiment is shown in FIG. 7. In this embodiment, the charge balancing diodes are formed inside the same trench as the gate. Trench **702** includes gate electrode **710** below which n-type **723** and p-type **725** silicon or doped polysilicon layers form pn junctions. A dielectric layer **708** separates the diode structure from gate terminal **702** as well as drift region **706**. As shown, there is no dielectric layer along the bottom of trenches **720**, thus allowing the bottom region **727** to be in electrical contact with the underlying region. In one embodiment, similar considerations to those dictating the design and manufacture of the gate oxide of MOS transistors are applied in designing and forming insulating layer **708**. For example, as in gate oxide of MOS transistors, the thickness of insulating layer **708** is determined by such factors as the voltage that insulating layer **708** is required to sustain and the extent to which the electric field in the trench diode is to be induced in drift region **706** (i.e., the extent of coupling through the insulating layer). The charge spreading in this embodiment is controlled by the optimization of the diode avalanche breakdown and the width of the depletion in the trenched diodes described more fully next.

As is well-known in this art, under reverse-bias conditions, the electric field is highest at the junction between regions **706** and **712** and linearly reduces in drift region **706** in the direction away from the junction between regions **706** and **712** at a rate dictated by the doping concentration of regions **712** and **714**. It is also well known that the larger the area under the electric field curve (i.e., the lower the rate at which the electric field reduces), the greater is the breakdown voltage. During operation, the diodes embedded in trenches **702** are reverse biased and thus the electric field is highest at the diode junctions (e.g., at the junction between opposite conductivity type regions **725** and **723**). Through insulating layer **708**, the electric field in the trench diodes induces a corresponding electric field in drift region **706**. The induced field is manifested in drift region **706** in the form of an up-swing spike and a general increase in the electric field curve in drift region **706**. This increase in the electric field results in a larger area under the electric field curve, which in turn results in a higher breakdown voltage.

It can be seen that by using multiple diodes in trenches **702**, multiple spikes can be induced along the depth of conduction regions in drift region **706**. This results in an electric field curve which tapers down from its highest level at a far lower rate than in conventional structures. An almost trapezoidal-shaped area can thus be obtained under the electric field curve in drift region **706** as opposed to the conventional triangular shape. A far greater breakdown voltage can thus be obtained.

When structure **700** is biased in the conduction state, current passes through conduction region of drift region **706**. By introducing diode trenches **702**, the electric field across the reverse-biased trenched diodes influences the charge distribution in adjacent drift region **706** such that a more uniform charge spreading is obtained in drift region **706**. By spreading the charge more uniformly in drift regions **706**, the silicon area taken up by drift region **706** is more efficiently used. Hence, for the same size drift region **706**, the portion of the

on-resistance attributable to the conduction region of drift region **706** is, in effect, reduced. This enables reducing the cell pitch for the same on-resistance. Accordingly, diode trenches **706** enable optimizing structure **700** to have higher breakdown voltage, lower on-resistance, and smaller cell pitch than can be achieved by conventional techniques.

Other variations of accumulation-mode transistor **700** are possible. One such variation is shown in FIG. **8**. In this embodiment, diode trenches **820** are disposed on either sides of gate trenches **802**, extending well into drift region **806**. Diode trenches **820** include one or more diode structures made up of opposite conductivity type regions **823** and **825** that form one or more pn junctions inside the trench. A thin dielectric layer **821** extending along the trench inner side-walls insulates the diodes in the trench from drift region **806**. In another variation of FIG. **8**, not shown, one or more charge electrodes are formed in the gate trench below the gate electrode.

An exemplary method of forming the structure in FIG. **8** is as follows. An n-type epitaxial layer is formed over substrate **814**. N-type region **812** is formed in the epitaxial layer by implanting dopants into the epitaxial layer. Depending on the desired doping concentration, n-type dopants may be implanted into the epitaxial layer so that channel regions **812** have a higher doping concentration than portion **806** of the epitaxial layer, or alternatively, p-type counter-dopants may be implanted into the epitaxial layer so that channel regions **812** have a lower doping concentration than portion **806** of the epitaxial layer. In another embodiment, regions **806** and **812** are formed by growing two n-type epitaxial layers having different doping concentrations. An exemplary set of process steps for forming the trenched diodes are described in the above-referenced commonly assigned patent application Ser. No. 10/821,796 titled "Schottky Diode Using Charge Balance Structure," filed Apr. 9, 2004, incorporated herein by reference in its entirety. The trenched-gate structures are formed using conventional techniques.

FIGS. **2-8** illustrate accumulation transistor embodiments in which various charge balancing structures are integrated in an optimum manner to improve the transistor blocking capability, on-resistance, and current density of the transistor. In FIGS. **9-14**, the transistor embodiment with the trenched electrodes as shown in FIG. **3** is used to show various structural modifications and features each with its own distinct advantages. Although FIGS. **9-14** show these structural modifications in the context of the trenched electrodes transistor embodiment of FIG. **3**, one or more of these structural modifications and features can be combined with one or more of the various charge balancing structures illustrated in FIGS. **2-8** depending on the desired goals and performance criteria.

In FIG. **9**, the channel regions in which the conduction channel is formed (e.g., regions **312** in FIG. **3**) are merged with the drift region to form a single region **906** in which trenches **902** are formed. Thus, drift region **906** extends from the top surface of the structure to substrate **914**. Transistor **900** operates in the same manner as transistor **300** in FIG. **3**. This embodiment has the advantage of a simpler manufacturing process because of elimination of the processing steps associated with forming the channel regions between the trenches. To maintain the same transistor current capability as the FIG. **3** structure, the doping concentration in region **906** needs to be increased. This in turn reduces the transistor voltage blocking capability. But, due to the presence of the charge balancing trenched electrodes, the increased doping concentration does not result in as much of a reduction in the transistor blocking capability. It is to be understood that the channel regions in the other embodiments illustrated in FIGS. **4-8** may similarly be merged with the drift region.

In FIG. **10**, heavily doped p-type regions **1018** are formed in channel regions **1012** between trenches **1002**. P-type

regions **1018** minimize the area of channel regions **1012** and reduce device leakage. P-type regions **1018** also allow for p+ contact which improve hole current flow in avalanche and improve device robustness. Each of p+ regions **1018** may be a single continuous region extending the length of the mesa (i.e., in the dimension perpendicular to the page) between trenches, or may be one of multiple p+ regions formed at intervals along the length of the mesa between the trenches. FIG. **11** shows a three-dimensional view of a variation of the structure in FIG. **10**. As shown, p+ regions **1118** laterally extend to abut the trenches between which they are located. However, p+ regions **1118** are formed at intervals along the length of the mesa so that channel regions **1112** can be contacted along their top surface in order to accommodate current flow when the transistor is turned on. An advantage of extending the p+ region between adjacent trenches as compared to FIG. **10** wherein p+ regions **1018** are laterally spaced from the trenches is that the alignment tolerance required by the spacing between the p+ regions and the edge of trenches in FIG. **10** is eliminated thus resulting in a smaller cell pitch. The p+ regions can be used in a similar manner in any one of the accumulation transistors described herein.

In FIG. **12**, n-type channel regions **1212** include more heavily doped shallow n+ source regions **1203**. Heavily doped source regions **1203** result in better contact with the overlying source electrode, and thus reduce the contact resistance. Heavily doped source regions **1203** can extend along the top surface of channel regions **1212** between trenches as shown in FIG. **12**, or can alternatively be formed as two regions adjacent trench sidewalls along the top edge of channel regions **1212** as shown in FIG. **13**. An advantage of this approach is the source metal contacting lightly doped channel regions **1212** forms a Schottky contact therebetween which helps minimize leakage current. FIG. **14** shows a 3-dimensional view of the structure illustrated in FIG. **13**. As shown, n+ source regions **1432** are formed at intervals along the length of the mesa between trenches in channel regions **1412**. N+ regions **1432** may alternatively be a single continuous region extending the length of the mesa between trenches. The heavily doped source regions as illustrated in FIGS. **12-14** can be used in the same manner in any one of the accumulation transistors described herein. The heavily doped regions in FIGS. **10-14** can be formed in respective channel regions using known masking and implanting techniques.

It is to be understood that any of the charge balancing structures illustrated in FIGS. **2-8** may be combined with one or more of the structural variations and features illustrated in FIGS. **9-14** as desired. For example, FIG. **15** shows the charge balancing structure illustrated in FIG. **7** in combination with the highly-doped p+ regions, wherein the channel regions are merged with the drift region to form a single silicon region **1506** in which the trenches are formed. FIG. **16** shows another example wherein the charge balancing structure illustrated in FIG. **2** is combined with the highly doped n+ regions.

Also, variations on exemplary vertical MOS-gated accumulation transistors have been discussed to illustrate the various features and advantages of the present invention. One of skill in the art appreciates that these can be implemented in other types of devices including planar-gate vertical transistors, planar-gate lateral transistors, trenched-gate lateral transistors, diodes, bipolar transistors and the like. FIGS. **17** and **18A-18C** show few examples of such devices. In FIG. **17**, laterally-positioned electrodes **1711a** and **1711b** are integrated in a planar-gate accumulation-mode lateral transistor **1700**. In FIGS. **18A-18C**, laterally-extending diode trenches **1820** are integrated in a planar-gate accumulation-mode lateral transistor **1800**. FIG. **18B** shows a top view of transistor **1800**. FIGS. **18A** and **18C** respectively show the cross section views along lines **18A-18A** and **18C-18C** in FIG. **18B**. In the

FIGS. 17 and 18A-18C embodiments, as in the previous embodiment, the charge balance electrodes and diodes extend parallel to the current flow.

FIG. 19 shows a cross-section view of a trench-gate accumulation FET 1900 in accordance with an embodiment of the present invention. FET 1900 includes an n-type substrate 1902, an n-type drift region 1904, and an n-type mesa region 1906. Gate trenches 1908 extend through mesa region 1906 and terminate in drift region 1904. Each gate trench 1908 is lined with a dielectric layer 1910 along its sidewalls and bottom, and includes a recessed gate 1912. N-type source regions 1914 flank each side of trenches 1908 as shown.

A p-type body region 1916 extends into mesa region 1906 between each pair of gate trenches 1908. Body regions 1916 form a p-n junction with mesa region 1906. The p-n junction results in a stronger pinch-off for improved blocking and R_{dson} . The amount of pinch-off, determined by the voltage and charge in the pinched-off region, influences the blocking characteristics. Also, the ratio of the pinched channel length (L_p in FIG. 19) to the pinched channel width (W_p in FIG. 19) needs to be kept as high as possible (preferably >1) for good blocking capability. Note that the pinched channel length L_p is the spacing between the bottom of region 1914 and the bottom of the shallower one of the gate 1912 and body region 1916.

In FIG. 19, body regions 1916 extend deeper than mesa region 1906, however, in another embodiment, a shallower body region (extending to a shallow depth within region 1906 or to a depth just above the lower surface of mesa region 1906) may be formed. But, a deeper body region, as shown, is advantageous since the built-in potential of the p-n junction ($V_{bi,max}$ value is E_g/q , $\sim 1.1V$) also pinches the channel thus resulting in better blocking capability. In other embodiments, each body region 1916 is advantageously formed as a continuous stripe along the dimension perpendicular to the page. Using a continuous stripe, as opposed to multiple body regions with gaps therebetween, prevents the possibility of leakage current to flow through the gaps. FIG. 23 more clearly illustrates an implementation of continuous body regions 2316 in one embodiment of the invention. In an alternate variation, the continuous body region is broken up into multiple regions, however the gaps between the body regions needs to be kept small enough so that the gaps can be fully depleted by the built-in potential. For cellular designs, each body region 1916 (FIG. 19) is enclosed within the cell such that it helps in pinching off the entire channel.

Incorporation of the body regions in the accumulation FET, in accordance with the different embodiments of the invention, results in a net built-in voltage which is about four times greater than that without the body regions. Hence the charge (Q) in the channel can be kept higher to obtain better on-resistance with high blocking capability. Since the accumulation layer mobility is higher than inversion layer mobility, the channel resistance is lower for accumulation FETs. This is particularly true for silicon carbide (SiC) based devices. Also, the pinched regions (i.e., the portions of mesa region 1906

between body region 1916 and its adjacent gate trenches 1908) can carry current, particularly at higher current densities, in parallel to the channel regions. This further lowers the R_{dson} thus improving device power handling capability and its efficiency. Also, due to higher transconductance and lower V_{th} , the accumulation FET in accordance with the invention is particularly attractive for low gate voltage, high current applications.

Conventional accumulation FETs rely solely on MOS depletion and hence are sensitive to oxide charge variations and work function differences. However, in the accumulation FET of the present invention, majority of the blocking is provided by the p-n junction, and thus the FET device is less sensitive to oxide charges. The threshold voltage (V_{th}) of the accumulation FET is primarily controlled by W_p (FIG. 19) and the doping concentration of mesa region 1906. In contrast, for conventional enhancement mode FETs, V_{th} is controlled by the T_{ox} , Q_{ox} , p-well dose/drive, source junction depth (X_{js}), and p-well junction depth (X_{jw}). Therefore, the V_{th} of accumulation FET of the present invention could be better controlled, particularly for low V_{th} devices.

The p-n diode formed between body region 1916 and mesa region 1906 injects minority carriers when forward biased and thus the associated reverse recovery may be undesirable in certain applications. This undesirable effect can be eliminated or substantially minimized in a number of ways. In a first approach, the doping concentration of body region 1916 is reduced. In a second approach illustrated in FIG. 20, a resistor 2018 is coupled between body regions 2016 and source regions 2014. Resistor 2018 drastically reduces the diode current, but still keeps body regions 2016 at ground potential during normal operation. The capacitance associated with the p-n junction needs to be charged through resistor 2018 during switching from on to off state. Thus, the resistance value of resistor 2018 should be carefully chosen such that the switching is not adversely affected while the injection of minority carriers is minimized. A third approach is to float body regions 2016 either by not biasing them to any potential, or as illustrated in FIG. 21, burying them in silicon. The latter approach completely eliminates the body diode problem.

FIG. 22 shows an exemplary implementation of an embodiment of the invention in a multi-pillar charge balance structure. In general, integrating super junction structures, such as that in FIG. 22, reduces the R_{dson} drastically. FIG. 23 shows an isometric view of an exemplary stripe geometry device with continuous body stripes 2316 and multi-pillar charge balance structure.

The table below compares simulation results for a 30V accumulation mode FET in accordance with an embodiment of the invention and a 30V conventional enhancement mode FET. No charge balance structure was used in either device. Simulation parameters used include: trench width=mesa width=0.5 μm ; T_{ox} =250 \AA ; trench depth=1 μm ; p-well/p-body depth=0.8 μm ; Epi thickness=2 μm ; Epi doping= $2 \times 10^{16}/cm^3$; doping of mesa region = $1 \times 10^{13}/cm^3$; BV is measured at $J=1 \text{ mA}/cm^2$; R_{dson} at $V_g=5V$, $J=100 \text{ A}/cm^2$; V_{th} at $J=10 \text{ mA}/cm^2$; and Q_{gt} at $V_g=5V$.

	Rsp; @ $V_g = 5V$, 100 A/cm^2 ($\mu\Omega\text{-cm}^2$)	V_{th} @10 mA/cm^2 (V)	BV @1 mA/cm^2 (V)	Body diode I _{rrm} (A)	Gm @ $V_{dd} = 2V$, $J = 100 \text{ A}/cm^2$ (S/cm^2)	Q_{gtot} @5V (nC/cm ²)
Accumulation FET	47.2	0.74	32.2	1.4	2427	1620
Enhancement FET	51.1	0.74	34.7	3.7	1676	1811

As can be seen, the accumulation FET has lower R_{sp} , Q_g and I_{rrm} , and a much higher transconductance (G_m) than the conventional enhancement FET. Also, simulation results showed that the electric field lines in the drift region of the accumulation FET had little crowding, were equally spaced and substantially flat, and as such similar blocking capability as the conventional FET was obtained.

Known process techniques can be used to form the accumulation FET of the present invention. For example, the manufacturing methods described above may be used and modified in one of a number of ways to obtain the structures shown in FIGS. 19-23. Body regions 1916 (FIG. 19) can be formed in a number of ways. In a first approach, multiple implants of p-type dopants into mesa region 1906 are carried out using varying energies to form body regions 1916 with a relatively uniform doping concentration and a rectangular profile with minimal lateral bulge. In a second approach, a trench may be formed through mesa regions 1906 between adjacent gate trenches 1908, and then selectively filled with p-type silicon using well known selective epitaxial growth (SEG) techniques. The latter approach provides good aspect ratio with a rectangular shape, and uniform doping concentration. These two techniques can be modified, as known in this art, to form the buried body regions 2120 in FIG. 21. Resistor 2018 in FIG. 20 may be formed in a number of ways. For example, a polysilicon thin film resistor may be used or alternatively the high metal contact resistance to lightly doped p-type body may be used as the resistor.

FIGS. 19-23 show the gate trenches terminating in the drift region, however, the gate trenches can also extend through the drift region and terminate within the substrate. While FIG. 23 shows an open cell geometry, the various embodiments of the invention may be implemented in any closed cell geometry, including hexagonal and square shape geometries. Also, while the various embodiments illustrated in FIGS. 19-23 are implemented in conventional silicon, these embodiments and their obvious variants can also be implemented in silicon carbide, gallium arsenide, gallium nitride, diamond or other semiconductor materials.

The cross-section views of the various embodiments described herein may not be to scale, and as such are not intended to limit the possible variations in the layout design of the corresponding structures. Also, the various transistors can be formed in stripe or cellular architecture including hexagonal or square shaped transistor cells

Although a number of specific embodiments are shown and described above, embodiments of the invention are not limited thereto. For example, it is understood that the doping polarities of the structures shown and described could be reversed and/or the doping concentrations of the various elements could be altered without departing from the invention. As another example, the various exemplary accumulation-mode vertical transistors described above have the trenches terminating in the drift regions, but they can also terminate in the more heavily doped substrate. As yet another example, the above-described embodiments are formed in silicon, but they could also be formed in silicon carbide, GaAs or other types of semiconductor materials. Also, the features of one or more embodiments of the invention may be combined with one or more features of other embodiments of the invention without departing from the scope of the invention.

Therefore, the scope of the present invention should be determined not with reference to the above description but should, instead, be determined with reference to the appended claim, along with their full scope of equivalents.

What is claimed is:

1. A method of forming an accumulation-mode field effect transistor, the method comprising:
 - forming a channel region of a first conductivity type in a semiconductor region of the first conductivity type, the channel region extending from a top surface of the semiconductor region to a first depth within the semiconductor region;
 - forming a gate trench in the semiconductor region, the gate trench extending from the top surface of the semiconductor region to a second depth within the semiconductor region below the first depth; and
 - forming a silicon region of a second conductivity type in the semiconductor region and extending to a third depth of at least the second depth such that the silicon region forms a P-N junction with the channel region along a wall of the silicon region.
2. The method of claim 1 wherein the silicon region and the gate trench are arranged so that the silicon region is laterally spaced from the gate trench.
3. The method of claim 1 wherein a conduction channel is formed in the channel region along a sidewall of the gate trench when the accumulation-mode field effect transistor is in an on state.
4. The method of claim 1 wherein the forming the silicon region includes:
 - forming a body trench in the semiconductor region, the body trench extending from the top surface of the semiconductor region to the third depth within the semiconductor region below the second depth; and
 - substantially filling the body trench with silicon material of the second conductivity type.
5. The method of claim 1 wherein the silicon region is formed by implanting a dopant of the second conductivity type into the semiconductor region.
6. The method of claim 1 further comprising:
 - forming a gate electrode in the gate trench, the gate electrode being adjacent to but insulated from the channel region.
7. The method of claim 1 wherein the semiconductor region includes an epitaxial layer extending over and in contact with a substrate, the substrate and the epitaxial layer being of the first conductivity type, the epitaxial layer having a lower doping concentration than the substrate, and
 - the channel region, the gate trench, and the silicon region extending into the epitaxial layer.
8. The method of claim 1 further comprising:
 - forming a source region of the first conductivity type in the channel region such that the source region flanks a side of the gate trench, the source region having a higher doping concentration than a doping concentration of the channel region.
9. The method of claim 8 further comprising:
 - forming a resistor coupled between the silicon region and the source region.
10. The method of claim 1 wherein a plurality of gate trenches including the gate trench and a plurality of silicon regions including the silicon region are disposed in parallel-extending continuous stripes.
11. The method of claim 1 wherein the silicon region is formed in the semiconductor region such that a top surface of the silicon region is below the top surface of the semiconductor region.
12. The method of claim 1 further comprising:
 - forming a column of silicon of the second conductivity type in the semiconductor region of the first conductivity type so that the column of silicon of the second conduc-

tivity type and the semiconductor region of the first conductivity type together form at least part of alternating columns of first and second conductivity type silicon, substantially no current flows through the columns of silicon of the second conductivity type when the accumulation-mode field effect transistor is in an on state.

13. The method of claim **12** wherein the column of silicon of the second conductivity type extends directly below a corresponding silicon region of the second conductivity type.

14. The method of claim **1** wherein the forming the silicon region of the second conductivity type includes forming the silicon region of the second conductivity type having a top surface that is coplanar with the top surface of the semiconductor region of the first conductivity type.

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